

# Symposium on Lift and Escalator Technologies

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## FOREWORD

It is with great pleasure that we present the proceedings of the 3<sup>rd</sup> Symposium on Lift and Escalator Technologies, September 2013, organised jointly by The Lift Engineering Section of the School of Science and Technology and The CIBSE Lift Group.

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

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

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

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

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

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



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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Converting the User Requirements into an Elevator Traffic Design: The *HARint* Space

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**Keywords:** Elevator, lift, round trip time, interval, up peak traffic, rule base, Monte Carlo simulation, average travel time, *HARint* Space, *HARint* plane.

**Abstract.** A previous paper introduced the concept of the *HARint* plane, which is a tool to visualise the optimality of an elevator design. This paper extends the concept of the *HARint* plane to the *HARint* space where the complete set of user requirements is used to implement a compliant elevator traffic design.

In the *HARint* space, the full set of user requirements are considered: the passenger arrival rate ( $AR\%$ ), the target interval ( $int_{tar}$ ), the average travelling time ( $ATT$ ) and the average waiting time ( $AWT$ ).

The *HARint* space provides an automated methodology in the form a set of clear steps that will allow the designer to convert these four user requirements into an elevator traffic design.

As with the *HARint* plane method, the target interval is used in combination with the expected arrival rate ( $AR\%$ ) and the building population,  $U$ , in order to find an initial assessment the number of passengers expected to board the elevator. The target average travelling time is then used to select a suitable elevator speed. This is then used to calculate the round trip time and then select the optimum number of elevators. An iteration is then carried out to find the actual number of passengers, and hence the elevator capacity. A check is then carried out to ensure that the average waiting time has been met, and if it has not been achieved, then a further iteration is carried out.

While the *HARint* plane provides the optimum number of elevator cars to achieve the two user requirements, the *HARint* space provides the optimum number of elevator as well as the optimum rated speed to meet the four user requirements of arrival rate, target interval, average waiting time and average travelling time.

An obvious consequence of the introduction of the average travelling time as a user requirement is that the speed becomes an outcome of the *HARint* space. The method also triggers a zoning recommendation in cases where the average travelling time cannot be met by varying the speed within reasonable limits.

## INTRODUCTION

The *HARint* plane [1] is a methodology that offers the elevator system designer a design methodology to arrive at an elevator design that meets the user requirements of arrival rate ( $AR\%$ ) and target interval ( $int_{tar}$ ). In addition, it offers the designer a graphical method to visualise the optimality of a design. Following the full set of steps allows the designer to arrive at an elevator design specifying the number of elevators and their car capacity (assuming a preset elevator rated speed).

The *HARint* plane methodology however is restricted to one rated speed. By covering a number of different speeds at the same time, the *HARint* space can show at the same time the optimal solution comprising the number of elevators, their rated speed and the car capacity, thus meeting four user requirements.

As with the *HARint* plane methodology, the *HARint* space methodology is applicable to incoming traffic conditions.

## THE HARINT SPACE METHODOLOGY

The *HARint* Space, like the *HARint* plane, uses two axes to represent the two most important user requirements: the target interval ( $int_{tar}$ ) and the arrival rate ( $AR\%$ ). The actual interval is represented on the  $x$ -axis and the handling capacity ( $HC\%$ ) is represented on the  $y$ -axis, corresponding to the two user requirements, respectively. The *HARint* plane is restricted to one rated speed. The *HARint* space on the other hand can represent a number of speeds at the same time.

Figure 1 shows an example of the plot of the *HARint* space. It can be noticed that there are two types of lines on the *HARint* space:  $P$  lines (curved lines shown in black) and  $L$  lines (nearly straight lines plotted in colours, green, red and blue).  $P$  stands for the number of passengers boarding the car in one round trip.  $L$  stands for the number of elevators in the group. These lines intersect at nearly right angles. The  $P$  lines pass through all the solutions that have the same number of  $P$  passengers. The  $L$  lines pass through all the solutions that have the same number of elevators in the group.

However, as different rated speeds are plotted, the  $P$  lines do not change with the change of speed, but there are as many  $L$  lines for each speed. The  $L$  lines have been shown in different colours, where each colour represents a different speed (as shown by the legend).

As with the *HARint* plane, the optimal solution should meet the two conditions shown in equations (1) and (2) below, with the smallest number of elevators and the lowest rated speed possible (in that order). But in addition it aims to meet the extra two requirements of the target average travelling time and target average waiting time, show in equations (3) and (4) below.

$$HC\% \geq AR\% \quad (1)$$

$$int_{act} \leq int_{tar} \quad (2)$$

$$ATT_{act} \leq ATT_{tar} \quad (3)$$

$$AWT_{act} \leq AWT_{tar} \quad (4)$$

The  $P$  curves and  $L$  lines shown in Figure 1 are based on the following numerical example:

### Building parameters:

$U= 1200$  persons (building population)

$N= 10$  floors (number of floors above main entrance)

$d_f= 4.5$  m (floor height)

### User requirements

$AR\%= 12\%$  (arrival rate as a percentage of the building population in 5 minutes)

$int_{tar}= 30$  s (the target interval)

$ATT_{tar} = 60$  s (the target average travelling time)

$AWT_{tar} = 10$  s (the target average waiting time)

### Kinematics

$v=1.6 \text{ m}\cdot\text{s}^{-1}, 2.5 \text{ m}\cdot\text{s}^{-1}, 4.0 \text{ m}\cdot\text{s}^{-1}$  (rated speed)

$a= 1 \text{ m}\cdot\text{s}^{-2}$  (rated acceleration)

$j= 1 \text{ m}\cdot\text{s}^{-3}$  (rated jerk)



Door timing

$$t_{do} = 2 \text{ s}$$

$$t_{dc} = 3 \text{ s}$$

Passenger transfer times

$$t_{pi} = t_{po} = 1.2 \text{ s}$$

An expanded view of the area of interest of the *HARint* space for this example is shown in Figure 2. It shows three *L* lines of interest and three *P* lines of interest. The three *L* lines are for 4, 5 and 6 elevators in the group. The three *P* lines are for 10.8, 14.4 and 18.0 passengers in the car. Notes that each *L* line comprises three coloured lines for the three speeds.

Figure 3 adds the average travelling time to the expanded view that was shown in Figure 2. Each *P* lines shows the value of the average travelling time corresponding to each speed. For example, the *P* line with  $P=18.0$  passengers, corresponds to an average travelling time of 74.4 s, 73.2 s and 73.2 s for the rated speeds of 1.6 m/s, 2.5 m/s and 4.0 m/s respectively. The round trip time can be evaluated using different methods and tools [2, 3, 4, 5, 6, 7]. The average travelling time can either be calculated using a formula for the simple cases [8] or using Monte Carlo simulation for the more complicated cases [9].

Figure 4 shows how the *HARint* space works in practice. If the *P* line  $P=14.4$  passengers is used, it leads to a solution shown on point A where the number of elevators in the group is 5, and the rated speed is 2.5 m/s. However, the average travelling time is not met (actual average travelling time is more than the 60 s target). The solution that meets all four user requirements is shown at point B where the actual travelling time is less than 57.5 s and the average waiting time is 3.8 s. This is achieved by using 6 elevators in the group and a speed of 2.5 m/s.

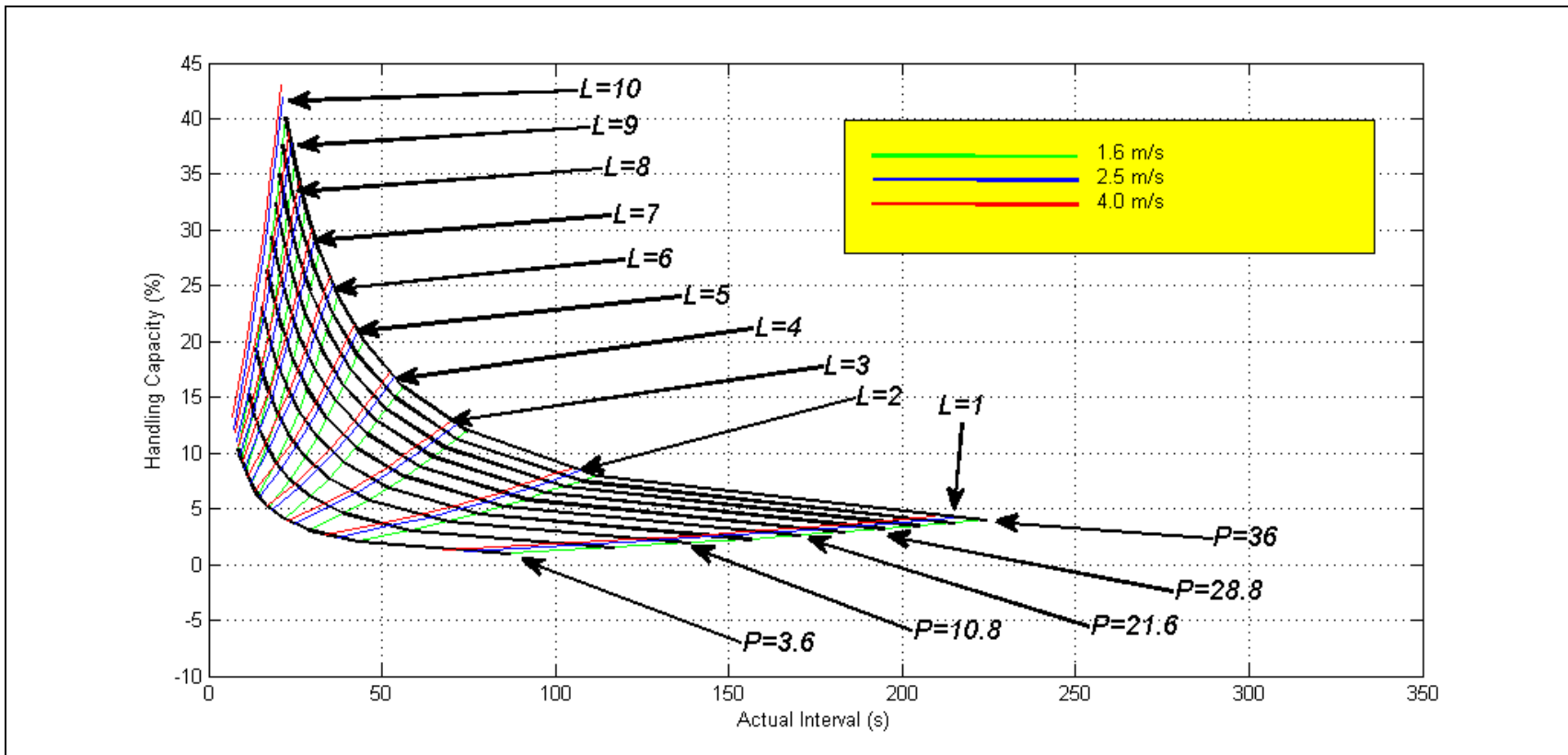


Figure 1: General overview of the *HARint* space for the example used.

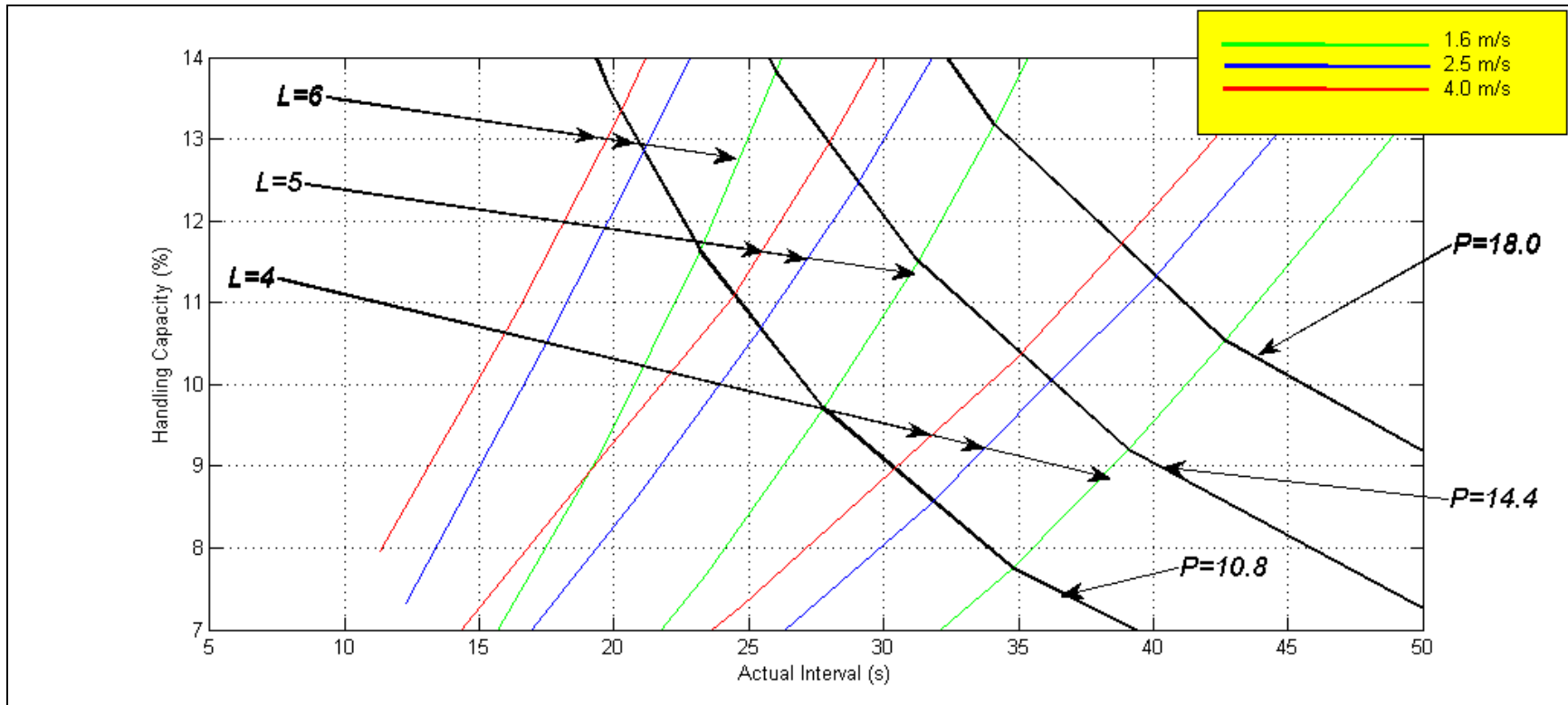


Figure 2: Enlarged view of the same *HARint* space for the example used.

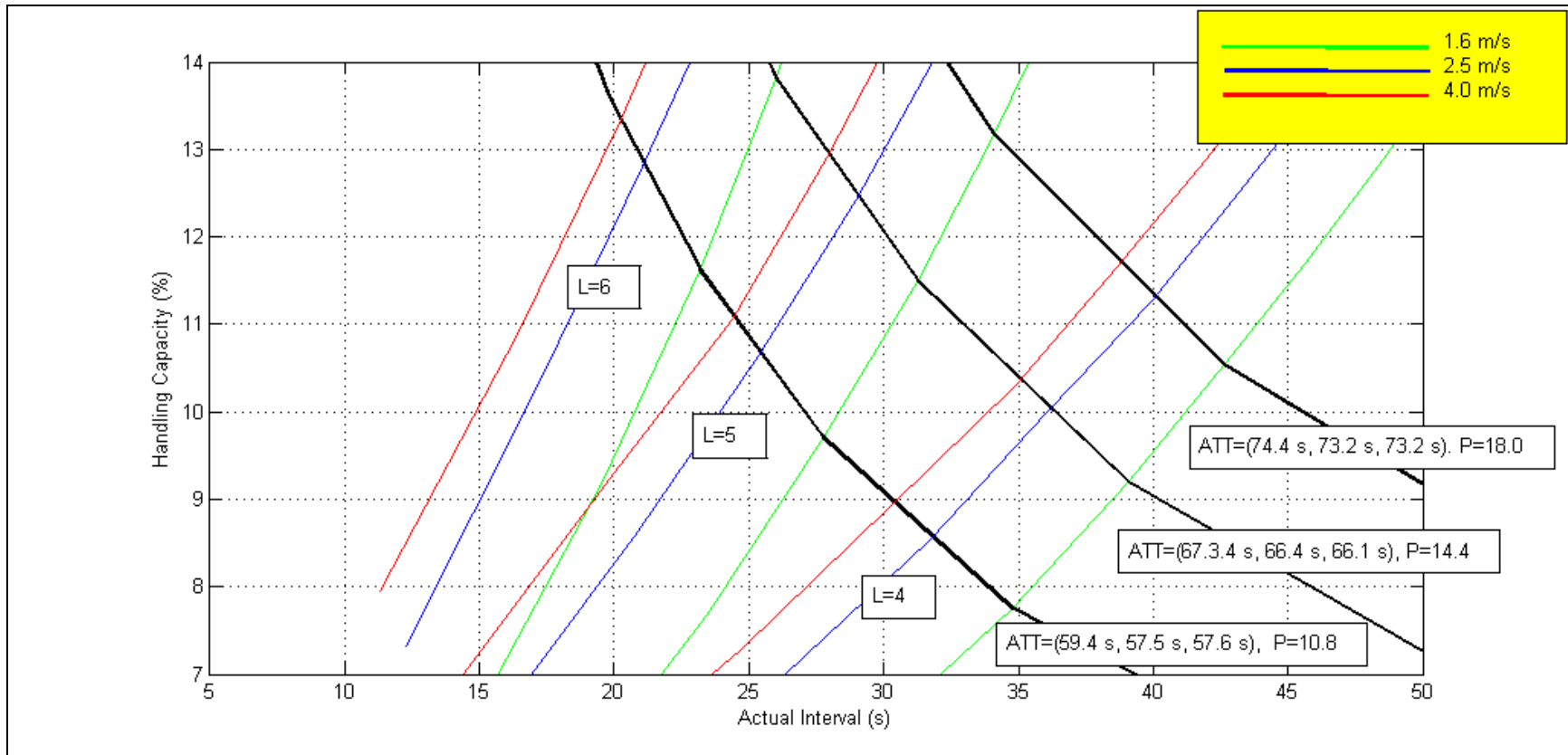


Figure 3: A view that shows that the constant  $P$  lines are also constant  $ATT$  lines.

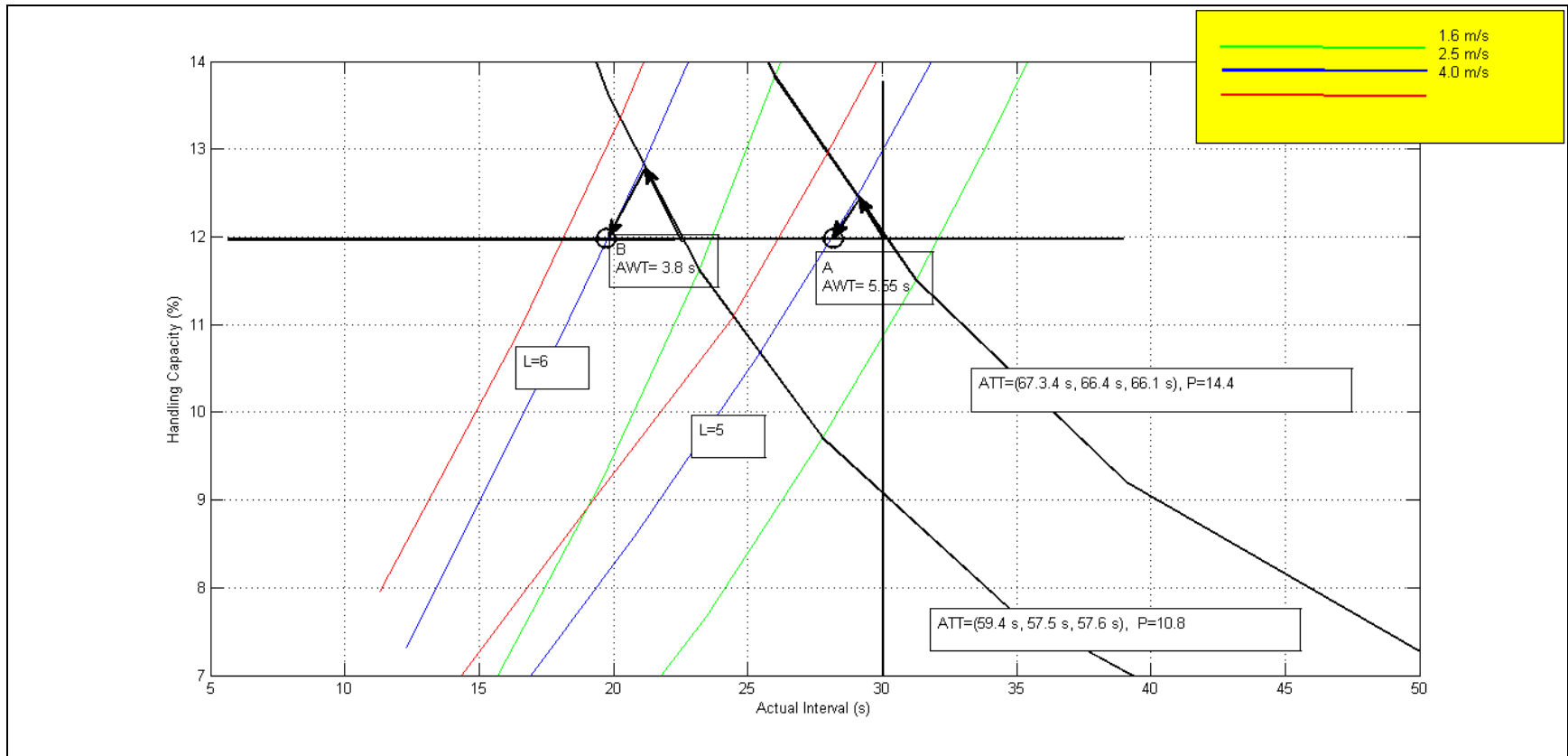


Figure 4: Two solutions A and B, one that meets the *ATT* requirement and one that does not.

## CONCLUSIONS

The HARint space has been presented as a methodology that uses four user requirements in order to develop a compliant elevator traffic design. It relies on graphical methods to visualise the final solution.

The four user requirements are: the passenger arrival rate ( $AR\%$ ), the target interval ( $int_{tar}$ ), the target average travelling time ( $ATT_{tar}$ ) and the target average waiting time ( $AWT_{tar}$ ).

A comparison is shown below in table format between the HARint plane method and the HARint space method. The HARint space offers the advantage that it provides the optimum rated speed and meets all the four user requirements instead of just two requirements as is the case in the HARint plane.

Category	The HARint Plane	The HARint Space
User requirements	<ul style="list-style-type: none"> <li>Arrival rate (<math>AR\%</math>)</li> <li>Target interval (<math>int_{tar}</math>)</li> </ul>	<ul style="list-style-type: none"> <li>Arrival rate (<math>AR\%</math>)</li> <li>Target interval (<math>int_{tar}</math>)</li> <li>Target average travelling time (<math>ATT_{tar}</math>)</li> <li>Target average waiting time (<math>AWT_{tar}</math>)</li> </ul>
Optimal outputs	<ul style="list-style-type: none"> <li>Number of elevators in the group (<math>L</math>)</li> </ul>	<ul style="list-style-type: none"> <li>Number of elevators in the group (<math>L</math>)</li> <li>The rated elevator speed (<math>v</math>)</li> </ul>
Byproduct output	<ul style="list-style-type: none"> <li>Car capacity (<math>CC</math>)</li> </ul>	<ul style="list-style-type: none"> <li>Car capacity (<math>CC</math>)</li> </ul>
Triggers		<ul style="list-style-type: none"> <li>Requirement for zoning based on target average travelling time.</li> </ul>

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Simplified Energy Calculations for Lifts Based on ISO/DIS 25745-2

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**Abstract.** It is often necessary to select the best performing lift installation in terms of energy efficiency, for example, to gain the first credit in the BREEAM classification system<sup>1</sup>. Previous energy consumption calculation methods have been inaccurate such as that suggested in CIBSE Guide D: 2010 [2]. A more accurate method has been developed by an International Standards Organisation Working Group (ISO/TC178/WG10) and this was published in ISO/DIS 25745-2 [3] on 6 June 2013. A simplified form of the calculation method is given here, together with a more exact method.

### 1 GIVEN DATA

The method relies on knowledge of three data sets: known data, measured data and estimated data.

Known data for the target installation is the design data. These data are: rated speed; rated load; acceleration value; jerk value, terminal floor to terminal floor distance; the number of stops; the time for the opening, opened and closing times of the lift doors at the landings; counter balancing ratio.

Measured data is obtained using the method specified in EN ISO 25745-1: 2012 [1] either from an actual target installation or a test tower facility set to emulate the target installation. These data are: running energy consumption in the reference cycle defined by the standard; standing idle energy consumption; standing standby energy<sup>2</sup>. In the absence of measured data, values obtained by simulation may be used.

Estimated data is an indication of the activity of the installation ranging from very low to very high activity. This data is represented by the number of trips per day.

### 2 ESTIMATED DAILY ENERGY CONSUMPTION

The estimated daily energy consumption ( $E_d$ ) of a lift is the sum of the running consumption ( $E_{rd}$ ) and the standing (idle/standby) consumption ( $E_{sd}$ ):

$$E_d = E_{rd} + E_{sd} \quad \dots (1)$$

### 3 ESTIMATED DAILY RUNNING ENERGY CONSUMPTION

The daily running consumption ( $E_{rd}$ ) is dependant on the energy used for an average trip that the target lift makes multiplied by the number of trips in a day ( $n_d$ ).

The running energy consumption ( $E_{rc}$ ) used to perform the ISO reference cycle<sup>3</sup> is given by the measurement made according to EN ISO 25745-1: 2012 [1].

---

<sup>1</sup> Other building classifications exist such as LEEDS, Green Star, etc.

<sup>2</sup> These terms are defined in BS EN ISO 25745-1: 2012

<sup>3</sup> The ISO reference cycle is an outwards travel of an empty car from one terminal landing to the other terminal landing and return.



This running energy measurement is for an empty car travelling the distance between the terminal landings ( $s_{rc}$ ). The distance travelled for an average trip ( $s_{av}$ ) is less than the distance between the terminal landings and can be expressed as a percentage of the distance ( $s_{rc}$ ), ie: as  $\%S = s_{av}/s_{rc}$ .

The running energy measurement is made with an empty car. In operation the lift will carry passenger loads from zero to full rated load. In general the average loading is low. For loaded cars the running energy needs to be multiplied by a load factor ( $k_L$ ). This factor is used to correct the value of energy consumption of lifts travelling empty in relation to an average load spectrum and is obtained multiplying the % of the trip ratio by the percentage of the reference trip energy consumed.

Thus the daily running consumption ( $E_{rd}$ ) in Wh is given by Equation 2:

$$E_{rd} = \frac{n_d \times \%S \times k_L \times E_{rc}}{2} \quad \dots (2)$$

where:

- $n_d$  is the number of trips per day<sup>4</sup>
- $\%S$  is the percentage average travel distance per trip for a target installation
- $k_L$  is the load factor per trip
- $E_{rc}$  is the measured or estimated running energy consumption of the ISO reference cycle (two trips) in Wh.

The number of trips per day ( $n_d$ ) for a target installation is either known, or can be estimated, or taken from ISO-Table 1 [3]. The number of trips defines the usage category for any calculations. ISO Part 2 includes an additional usage category (Category 6)

The tables available in ISO/DIS 25745-2 correspond to average buildings with an homogeneous distribution of the population per floor and no express zones, in which the lift service out of the working hours and during the weekends follow general patterns for offices and for residential buildings. When the target building has an inhomogeneous distribution of the population or shows an unconventional operation it may be necessary to perform on site traffic measurements or simulations. The load factors of the standard also include an estimation of the traffic distribution.

**ISO-Table 1: Categorized number of starts per day<sup>5</sup>**

Usage category	1	2	3	4	5
Usage intensity	very low	low	medium	high	very high
Number of trips per day ( $n_d$ )	50	125	300	750	1500
Typical range	<75	75-200	200-500	500-1000	1000-2000

The percentage average travel distance ( $\%S$ ) can be taken from ISO-Table 2 [3] based on the usage category selected and the number of possible stops in the served building.

<sup>4</sup> A trip is a movement from one floor to another.

<sup>5</sup> The ISO standard has a usage category 6, which is greater than 2000 trips per day and which is not considered here as it is only likely to arise in extreme circumstances.

**ISO-Table 2: Percentage of average travel distance (%S)**

Usage category	1 – 4	5
<b>Number of stops</b>	<b>Percentage average travel distance</b>	
<b>2</b>	100%	
<b>3</b>	67% #	
<b>&gt;3</b>	44%	33%

# The value suggested may need to be reviewed, if the traffic movement between the two terminal floors is dominant. In this case the average travel distance may tend towards 100%.

Note the number of stops for the target installation is a known data.

The value for the load factor ( $k_L$ ) can be calculated using ISO-Equations 3a – 3e below, where the value for percentage average car load (% $Q$ ) is taken from ISO-Table 3 [3] according to the usage category and the rated load.

Note the rated load ( $Q$ ) of the target installation is a known data.

**ISO-Table 3 Average car load**

Usage category	1 - 3	4	5
<b>Rated load (kg)</b>	<b>Percentage of rated load (%<math>Q</math>)</b>		
<b>≤ 800</b>	7.5	9.0	16.0
<b>801 – ≤1275</b>	4.5	6.0	11.0
<b>1276 – ≤ 2000</b>	3.0	3.5	7.0
<b>&gt;2000</b>	2.0	2.2	4.5

For traction lifts counter balanced to 50%

$$k_L = 1 - (\%Q \times 0.0164) \quad \dots (3a)$$

Range 0.97 – 0.74.

For traction lifts counter balanced to 40%

$$k_L = 1 - (\%Q \times 0.0192) \quad \dots (3b)$$

Range 0.96 – 0.69.

For hydraulic lifts with no counter balancing

$$k_L = 1 + (\%Q \times 0.0071) \quad \dots (3c)$$

Range 1.02 – 1.11.

For hydraulic lifts with 35% counter balancing of the car weight

$$k_L = 1 + (\%Q \times 0.0100) \quad \dots (3d)$$

Range 1.02 – 1.16.

For hydraulic lifts with 70% counter balancing of the car weight

$$k_L = 1 + (\%Q \times 0.0187) \quad \dots (3e)$$

Range 1.04 – 1.30.

The first three equations represent common traction and hydraulic lifts. The parameters given in these equations were developed from a computer model of a lift system applying a simple traffic pattern for a set of lift loads. More sophisticated traffic patterns can result in different load factors. The range shown is for the lowest and highest %Q values in ISO-Table 3 [3]. It should be noted that a load in a traction lift reduces energy usage and in a hydraulic lift increases energy usage.

#### 4 ESTIMATED DAILY STANDING ENERGY CONSUMPTION

The daily standing (idle/standby) energy consumption comprises two main components:

$$E_{sd} = (24 - \frac{n_d}{3600} t_{av}) (P_{id} R_{id} + P_{st} R_{st}) \quad \dots (4)$$

where:

- $P_{id}$  is the power used when the lift is in idle mode (W)  
(measured after door operations have ceased when stopped at a landing.)
- $P_{st}$  is the power used when the lift is in standby mode (W)  
(measured after 5 minutes of inactivity.)
- $R_{id}$  is the ratio of idle time when consuming  $P_{id}$  (value<1)
- $R_{st}$  is the ratio of standby time when consuming  $P_{st}$  (value<1)
- $t_{av}$  is the time to travel the average travel distance for the target installation, including door times (s)

Note the first term in Equation 4 is the time the lift is not running, ie: standing.

The idle power and the standby power are measured values obtained by the method given in EN ISO 25745-1: 2012 [1]. The idle power is measured with an empty car and when door operations have ceased. Standby power is measured after 5 minutes of inactivity.

The ISO method considers systems that may stay in a second standby mode up to 30 minutes. This not considered here.

The values for  $R_{id}$  and  $R_{st}$  can be taken from ISO-Table 4 [3].

The time ( $t_{av}$ ) to travel the average distance ( $s_{av}$ ) is given by Equation 5:

$$t_{av} = \frac{s_{av}}{v} + \frac{v}{a} + \frac{a}{j} + t_d \quad \dots (5)$$

where:

- $v$  is the rated speed (m/s)
- $j$  is the rated jerk (m/s<sup>2</sup>)
- $t_d$  is the time for the opening, opened and closing times of the lift doors at the landings (s)

**ISO-Table 4: Time ratios in idle and standby modes**

Usage category		1	2	3	4	5
Time ratios (<1)	$R_{id}$	0.13	0.23	0.36	0.45	0.42
	$R_{st}$	0.87	0.77	0.64	0.55	0.58

## 5 EXAMPLES

### 5.1 Example 1 – traction lift

(from SAFE S24<sup>6</sup> with rounded values for easier arithmetic)

#### Lift parameters

Traction lift in an office building

Rated load 1,600 kg

Rated speed 2.50 m/s

Travel 75 m

Number of stops 20

Counterbalancing 50%

Acceleration 1.0 m/s<sup>2</sup>

Jerk 1.25 m/s<sup>3</sup>

Door times 8.0 s

#### Data determined by measurement or simulation

Idle power 500 W

Standby power after 5-minutes 120 W

ISO reference cycle energy 170 Wh

#### Estimated Data

Daily trips 1500 (category 5)

#### Data from tables

Average travel distance 33% [from Table 2]

Average car load 7.0% [from Table 3]

Load factor ( $k_L$ ) 0.89 [from  $k_L = 1 - (\%Q \times 0.0164)$ ]

Idle/Standby time ratio 42/58 [from Table 4]

#### Calculation of daily running energy consumption

$$E_{rd} = \frac{n_d \times \%S \times k_L \times E_{rc}}{2} = \frac{1500 \times 0.33 \times 0.89 \times 170}{2}$$

$$= 37,447 \text{ Wh}$$

#### Calculation of daily standing energy consumption

$$s_{av} = 0.33 \times 75 = 25 \text{ m}$$

$$t_{av} = 25/2.5 + 2.5/1 + 1/1.25 + 8 = 21.3 \text{ s}$$

$$E_{sd} = \left(24 - \frac{n_d}{3600} t_{av}\right) (P_{id} R_{id} + P_{st} R_{st}) = \left(24 - \frac{1500}{3600} 21.3\right) (500 \times 0.42 + 120 \times 0.58)$$

$$= 4,229 \text{ Wh}$$

#### Calculation of daily energy consumption

$$E_d = 37,447 + 4,229 = 41,676 \text{ Wh}$$

This is 42 kWh per day<sup>7</sup>.

<sup>6</sup> SAFE Swiss Federal Office of Energy, 2005. <http://www.electricityresearch.ch>.

<sup>7</sup> About 0.4p (0.4c) per trip!

## 5.2 Example 2 – hydraulic lift

(from SAFE S3 with rounded values for easier arithmetic)

### Lift parameters

Hydraulic lift in a residential building

Rated load 500 kg

Rated speed 0.6 m/s

Travel 13 m

Number of stops 5

Counterbalancing 0%

Acceleration 0.3 m/s<sup>2</sup>

Jerk 0.5 m/s<sup>3</sup>

Door times 8.0 s

### Data determined by measurement or simulation

Idle power 50 W

Standby power after 5-minutes 31 W

ISO reference cycle energy 91 Wh

### Estimated Data

Daily trips 30 (category 1)

### Data from tables

Average travel distance 44% [from Table 2]

Average car load 7.5% [from Table 3]

Load factor ( $k_L$ ) 1.05 [from  $k_L = 1 + (\%Q \times 0.0071)$ ]

Idle/Standby time ratio 13/87 [from Table 4]

### Calculation daily running energy consumption

$$E_{rd} = \frac{n_d \times \%S \times k_L \times E_{rc}}{2} = \frac{30 \times 0.44 \times 1.05 \times 91}{2}$$

$$= 631 \text{ Wh}$$

### Calculation daily standing energy consumption

$$s_{av} = 0.44 \times 13 = 5.7 \text{ m}$$

$$t_{av} = 5.7/0.6 + 0.6/0.3 + 0.3/0.5 + 8 = 20.1 \text{ s}$$

$$E_{sd} = (24 - \frac{n_d}{3600} t_{av}) (P_{id} R_{id} + P_{st} R_{st}) = (24 - \frac{30}{3600} 20.1) (50 \times 0.13 + 31 \times 0.87)$$

$$= 797 \text{ Wh}$$

### Calculation daily energy consumption

$$E_d = 631 + 797 = 1,428 \text{ Wh}$$

This is 1.4 kWh per day<sup>8</sup>.

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<sup>8</sup> About 0.7p (0.7c) per trip!

## 6 A MORE ACCURATE CALCULATION

The figures given in ISO-Tables 2, 3 and 4 are based on the median values for the usage category obtained using statistical smoothing techniques. If the usage is discovered to be at the lower or higher end of a category then using the median value may be inaccurate.

Thus if the actual number of trips is not close to the median it is suggested that values could be obtained from the tables by interpolation or for more accuracy by using the graphs [4] from which these tables have been derived [5].

It may be necessary, for example, that in order to obtain credits under BREEAM a more accurate calculation is required (for example by means of simulations).

Suppose the installation in Example 1 had either 1,000 or 2,000 number of starts per day, instead of the median of 1,500 starts per day. These duties are at the extreme ends of the Usage Category 5.

What then are the values for average travel distance, average car load and the idle/standby time ratio?

Figure 1 shows a fuller presentation of the average distance travelled -v- number of starts.

Figure 2 shows a fuller presentation of average load transported -v- number of starts and rated load.

Figure 3 shows a fuller presentation of the ratios of running, idle and standby times.

With all other data remaining the same consider 1000 and 2000 starts per day. Carrying out the calculations Table 5 gives a comparison.

**Table 5: Calculations using Figures 1 – 3**

<b>Number of starts per day</b>	<b>1500</b>	<b>1000</b>	<b>2000</b>
Average travel distance	33% [from Table 2]	44% [from Figure 1]	30% [from Figure 1]
Average car load	7.0% [from Table 3]	3.5% [from Figure 2]	12.5% [from Figure 2]
Load factor ( $k_L$ ) [from $k_L = 1 - (\%Q \times 0.0164)$ ]	0.89	0.94	0.80
Idle/Standby time ratio	42/58 [from Table 4]	34/66 [from Figure 3]	45/55 [from Figure 3]
Daily running energy consumption	37.5 kW	35.2 kW	40.8 kW
Daily standing energy consumption	4.2 kW	4.3 kW	3.7 kW
Daily energy consumption	41.7 kW	39.5 kW	44.5 kW

The simple method proposed in ISO/DIS 25745-2 gives a daily energy consumption of 41.7 kW. If the extremes of Usage Category 5 are considered then the energy consumption ranges from 39.5 kW at the low end to 44.5 kW at the high end.

## 7 DISCUSSION

In observing Table 5 it can be seen that there is a smaller consumption for the smaller number of starts and a higher consumption for the larger number of starts. In this case they represent -5.5%/+6.7%. Thus in this case the accuracy of the median value is better than 10%.

It is worth noting that the average car load for the highest number of starts is still very low at 12.5%. This observation supports the concept that in off peak periods of time some of the lifts in a group should be shut down (in sequence to balance wear and tear) to ensure cars are loaded towards balance. This reduction of the number of lifts in service should however provide acceptable passenger waiting times at all times.

## 8 CONCLUSIONS

This paper has presented a method of calculating daily energy consumption following the proposals contained in the ISO/DIS/25745-2 [3]. This method is the most accurate method for general classification purposes so far proposed in the public domain (see review of the state of the art of energy estimation methods in [5]). It does involve obtaining values for a number of parameters on site, in a test tower or by computer modelling. The final value obtained is totally dependent on the value of the exact number of trips ( $n_d$ ) being known from measurement or specification.

The simplified method using Equation 2 plus Equation 4 produces good results, but it is less accurate than using the graphs.

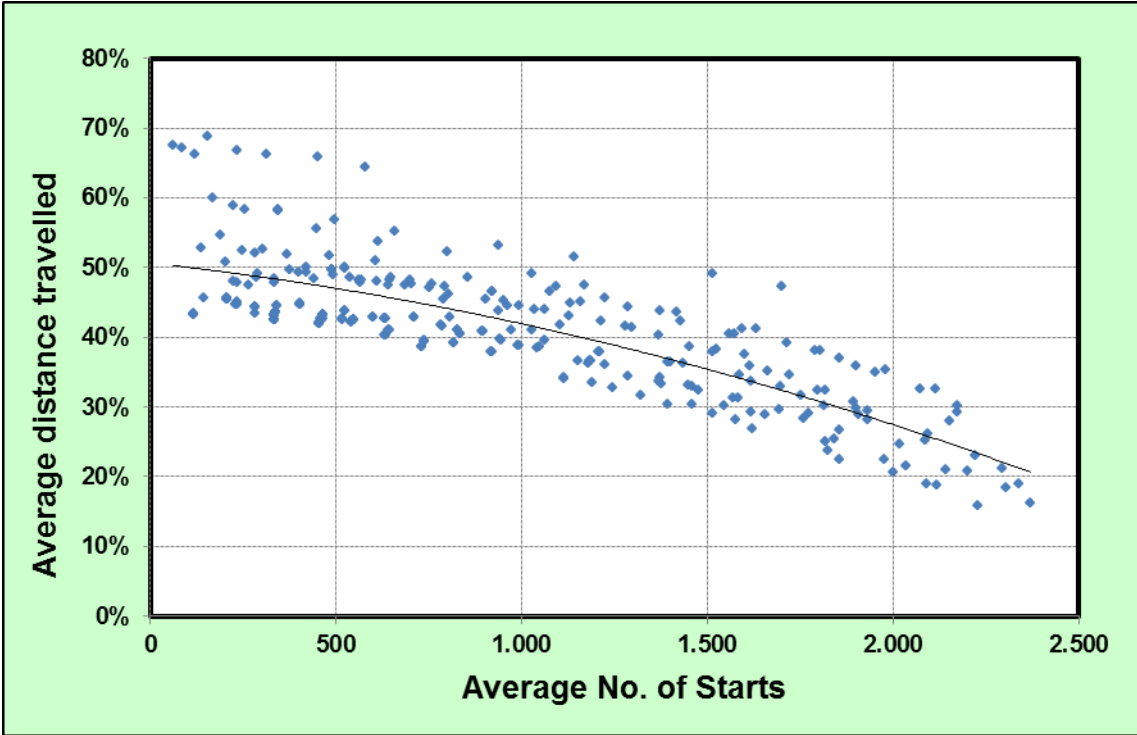
For practical purposes, the lift manufacturer can measure in a test tower all the travel distances appropriate to the product range in order to be able to provide values for the energy consumed for an ISO Reference Cycle ( $E_{rc}$ ).

## REFERENCES

- [1] BS EN ISO 25745-1: 2012 *Energy performance of lifts, escalators and moving walks Part 1: Energy measurement and verification*
- [2] CIBSE Guide D: 2010 *Transportation systems in buildings*.
- [3] ISO/DIS 25745-2: 2013 *Energy performance of lifts, escalators and moving walks Part 2: Energy calculation and classification for lifts (elevators)*
- [4] Lorente, A-M, Nunez, J.L & Barney G.C.: *Energy models for lifts*; 2nd Symposium on Lift and Escalator Technologies, 27 September 2012, The University of Northampton and WWW.ELEVATORWORLD.COM, April 2013.
- [5] Lorente, A-M, doctorate thesis to be submitted to the University of Zaragoza entitled: *Life Cycle Analysis and Energy Modelling of Lifts*

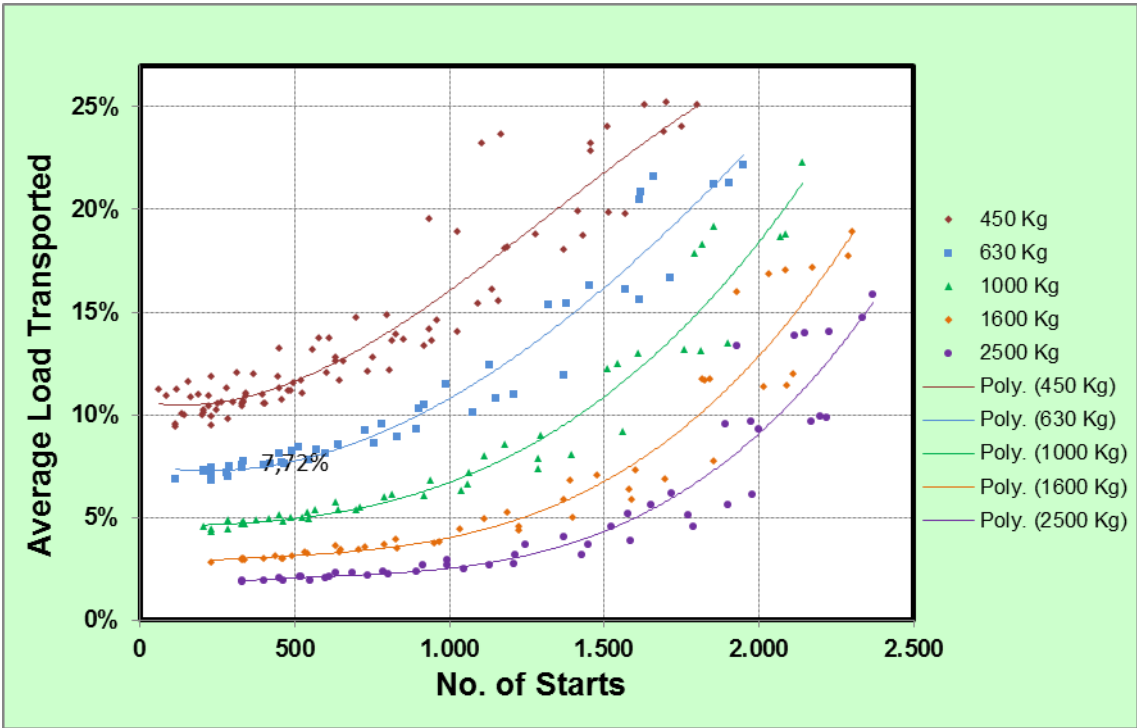
## ACKNOWLEDGEMENTS

ISO/TC178/WG10 for developing the method. The Task Group of WG10 for developing the load factor ( $k_L$ ). The tables contained in the standard were developed by Ana Lorente [5] as part of her doctorate studies at the University of Zaragoza, Spain in support of the work of WG10 and are described in Reference 4.



**Figure 1: Average distance travelled -v- number of starts**

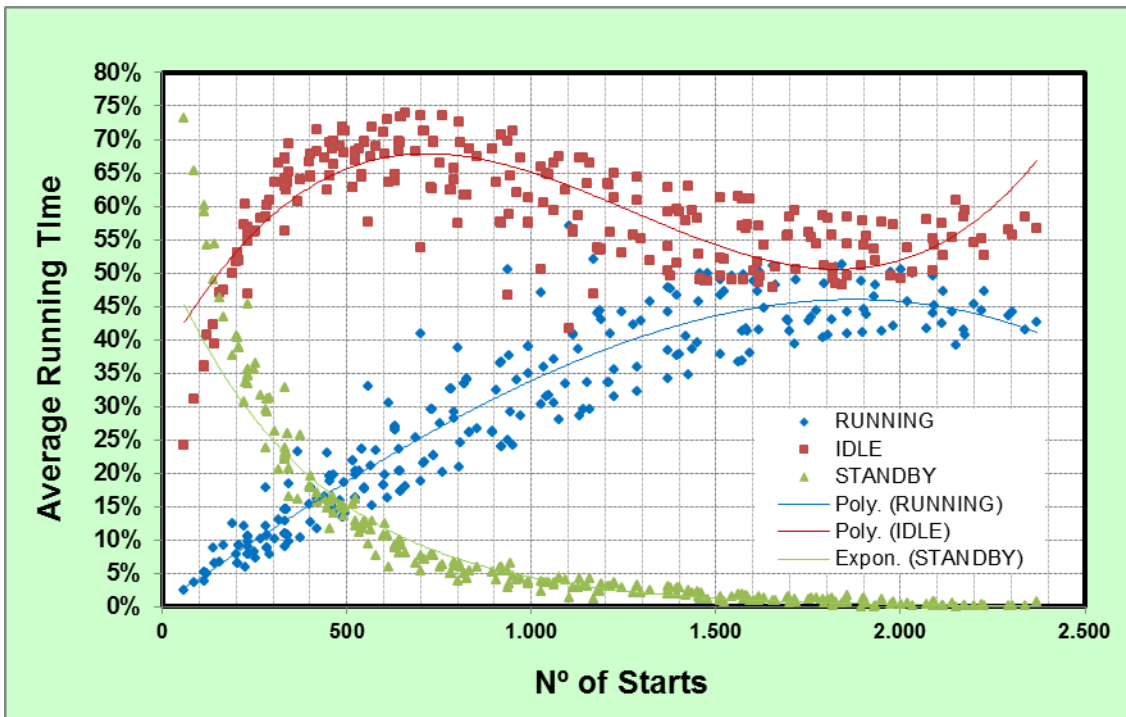
Observe that as the number of starts increases the average distance travelled falls.



**Figure 2: Average load transported -v- Number of starts for various rated loads**

Observe that as the number of starts increases the average load increases.





**Figure 3: Ratios of running, idle and standby times.**

The total running + idle + standby should equal 100%, but may not be exactly so owing to statistical variations. As the number of starts increase the standby falls towards zero leaving running and idle times as roughly equal components. The reason for the turnover at the highest number of starts is due to installation saturation in the face of exceptionally severe traffic demands.

# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Passenger flow pattern learning based on trip counting in lift systems combined with real-time information

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**Abstract.** Conventional Control in vertical transportation systems may use information about passenger flows in order to estimate the number of passengers behind each landing call and to assess the destination of these possible passengers. This information supports the lift dispatching algorithm by giving it the opportunity to implement specific strategies for different circumstances. This paper proposes a new method to identify passenger flows in advance, using historical trip counting information summarized into origin destination matrices for short periods of time. Using these matrices, a clustering procedure can identify periods of homogeneous flow present in the data, learning the main traffic flow and providing a long-term view about the traffic profile in which the system is working. Real-time information about the traffic measurements extracted from the information transmitted to the dispatching algorithm can provide the short-term view. By mixing long-term and short-term information it is possible to estimate the expected values of the unknown quantities. The benefits of this process are tested against the Multiple Travelling Salesman Problem (MTSP) where the salesman corresponds to cars and the cities correspond to landing and car calls. The MTSP is the core of a stochastic bi-level optimization problem when the genetic algorithms are applied to the lift dispatching problem.

## INTRODUCTION

The lift dispatching problem is a real-time optimization problem similar to high-rack warehouses and dispatching service vehicles where the assignment can change and the decision must be taken before all the information is known [1]. The decision taken by this type of system can be considered partially revocable in that assignments can be changed up to the point at which a lift starts to decelerate to serve a call. As a new request arrives, the system can compute a new schedule for the current set of requests, replace the old schedule by the new one and follow this schedule until it is finished or replaced.

With conventional control, the lift dispatching problem suffers from a lack of information. From outside the car, the landing call provides the start floor of the trip, travel direction, and landing call time, but the number of passengers, their arrival times and the destination floors are unknown. From inside the car, the destination floor is known, but the number of passengers alighting at each floor is unknown.

A common assumption can be that nothing is known about the future. Applying this assumption, one request corresponds to only one passenger and the destination of this passenger can be any floor. When a car arrives to answer a call, it may not have enough capacity to transport all the passengers, in which case the remaining passengers will re-register their call.

To avoid this, missing information can be added using the assumption that continuously operating systems should exhibit some level of repeatability. In this case, the passenger flow pattern can record this information. It is commonly accepted that a Poisson process can be used to model the arrival of passengers [2, 3]. Later research suggests that people move around and use lifts in batches. On the other hand, if we assume that passengers travelling through specific buildings follow approximately the same pattern day after day, we can take advantage of this stability. The system can analyse information about trips previously completed, looking for a passenger flow pattern [4, 5, 6, 7].

Due to the fact that fast response times are required of a dispatching algorithm, the system analysing the flow pattern can be designed as an off-line algorithm. It can perform a data extraction process and summarise passengers' information for different trips in the same time interval giving improved estimates for the MTSP [8].

The information required is the number of passengers behind every landing call as well as their destinations. Previous work used detailed log data to extract information about the origin and destination of the passenger trips, working towards a complete information system [9].

We will introduce details of the passenger trip data counting process, the indicator and the passenger profile used to test it. Then we will show how this information can be amended in real time, assuming we have the information necessary to synchronize off-line information about the passenger flow pattern and real-time information about the people entering the system.

## **PASSENGER FLOW DATA PATTERN LEARNING**

Counting passenger trip data is the first step to learning the passenger pattern flow. The flow pattern will record the number of passengers moving from an origin floor to a destination floor in a given time interval. To implement this first step, a simulation tool has been applied. Simulation represents an ideal situation, not a real one, and we understand that results need to be verified in a real situation.

The methodology used to learn the passenger flow pattern is as follows:

- Select a passenger profile that includes different traffic patterns: incoming, outgoing, interfloor. Table 1 shows the profile that has been used for the simulations completed for this paper. The profile has been designed to include a range of traffic patterns. The first 4 periods represent an up-peak (majority incoming traffic). Interfloor traffic is represented in periods 5, 6, 10, 11 and a lunch peak in periods 7, 8, 9. Finally down peak (majority of outgoing) is represented by the last 4 periods.

Period	%Pop per 5 mins	%Incoming	%Outgoing	%Interfloor
1	5	85	10	5
2	8	85	10	5
3	13	85	10	5
4	5	85	10	5
5	2	10	10	80
6	2	10	10	80
7	1	50	50	0
8	13	50	50	0
9	1	50	50	0
10	2	10	10	80
11	2	10	10	80
12	5	10	85	5
13	13	10	85	5
14	8	10	85	5
15	5	10	85	5

**Table 1 Mixed passenger flow profile**

- Execute any algorithm available in the platform 10 times with the same passenger traffic profile but different random number seeds (1 to 10), then extract a log file for the passenger trip counting process. This log is the basis of the counting. It has all the information that the passenger introduces to the system and also all the movements and data of the lifts [10].
- Extract the origin destination matrices for each log file; they will record the movements from origin to destination for every day aggregated for the considered time interval. The time interval used will be 2.5 minutes. The data obtained counting passenger trips from log data is very close to the real data and we can say that in an ideal situation, the error in the counting process is less than  $\pm 10\%$ . In the Eq. 1, it can be seen how to obtain the Origin Destination (OD) matrix in order to obtain the value of each floor.

$$\text{EntranceData}_F = \sum_{j=1}^{\text{num\_floors}} OD_{F,j} \quad (1)$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	Total		
REAL	27	0	0	1	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	1	0	1	0	1	38
COUNT	27	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	0	1	0	1	1	1	0	0	0	0	1	0	0	0	0	1	0	1	0	1	39

**Fig. 1 Comparison of the entrance data for the real and counted across OD data**

- Learn a passenger flow pattern using this 10 days of information, analyse the homogeneous periods of traffic over origin destination matrices [11] and learn the traffic flow pattern [12,13]. This step has been simplified, selecting as a pattern one random day OD matrix.
- The learned pattern can be used in very different ways to feed a dispatching algorithm, one of the simplest ways to do it is by looking only at the number of people that have arrived at every floor for every time interval. It will be mixed with real time information as explained in the next sections.

- Analyse how to incorporate this information in the MTSP and measure the benefits.

## DYNAMICALLY ESTIMATING PASSENGER FLOW DATA USING REAL TIME CAB LOAD AND LEARNED PATTERN.

The real time information [14] will be the estimated number of passengers entering the system at each floor that is recorded in a variable called *Origin*. The variable origin has a count of passengers that have been answered in the last 50 seconds, the interval time, for any lift. This data is separated according to the trip direction (up, down) Fig. 2.



Fig. 2 Origin data Structure

The lift stops are found for the interval time and at each stop the passenger transfers are counted. This count continues until the lifts start moving again, as shown in Eq. 2 and Eq. 3.

$F$ : set of floors

$$\text{Origin}_{\text{up},F} = \sum_{l=1}^{\text{num\_cars}} \left( \sum_{t=1}^{50} q_{l,t} \right) \quad \text{for trips in up direction} \quad (2)$$

$$\text{Origin}_{\text{down},F} = \sum_{l=1}^{\text{num\_cars}} \left( \sum_{t=1}^{50} q_{l,t} \right) \quad \text{for trips in down direction} \quad (3)$$

Where  $q$  represents the load, which later is transferred into number of passengers. The direction of these trips is known because of the landing calls. The count is performed over every lift and then, summarized, and recalculated every interval time.

Mixing this real time information with the previously learned profile, will pull together long term (OD matrices aggregated for an interval time of 2.5 minutes) and short term information (Origin aggregated for an interval time of 50 seconds, a third of the long term information). Fig. 3 graphically represents what each one represents. The OD data is read from a file and Origin is calculated while the system is running. OD matrices summarize the trips expected to be performed within the time interval, whereas Origin calculates the weight entered in the system in the previous time interval. Ways to combine these can be found in the literature [15].

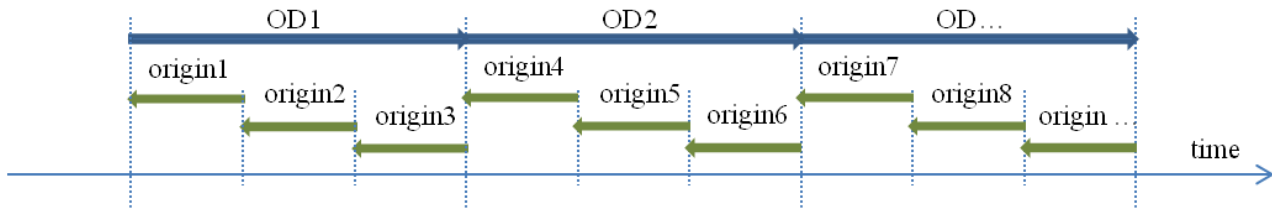


Fig. 3 Joining the OD and the Origin data

As it can be seen, the OD matrix gives future information while the origin data provides information of the recent past events. The OD data has been divided in three parts so that we can compare 3 sets of short term data with the learned profile. Before dividing the matrix, it has to be separated into up and down passenger movements as shown in Eq. 4 (up) and Eq. 5 (down). Fig. 4 represents graphically how the division of the OD is made.

$$\text{OD}_{\text{up},F} = \sum_{i=1}^{\text{num\_floors}} \left( \sum_{j=i+1}^{\text{num\_floors}} \text{OD}_{i,j} \right) \quad (4)$$

$$OD_{down,F} = \sum_{i=1}^{num\_floors} \left( \sum_{j=i+1}^{num\_floors} OD_{j,i} \right) \quad (5)$$

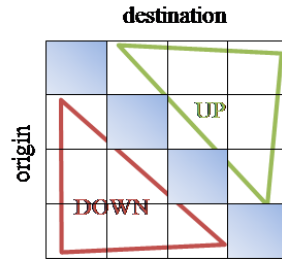


Fig. 4 OD matrix

In this way, the OD has been converted to the same style as the origin data. One side provides the number of up direction passengers and the other, the down direction passengers. This data has been converted into count the passengers moving from each floor in up or down directions. Now is possible to divide the OD in 3 parts, see Fig. 5. These 3 parts are exactly the same, because it is assumed that the passengers will arrive constantly in the 2.5 minute time interval.

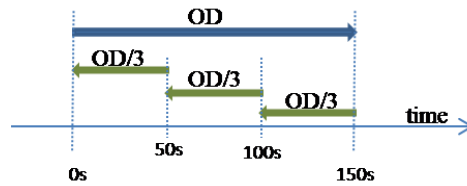


Fig. 5 Representation of the OD data in the origin format

### How to estimate the passengers for the next time interval

To start the estimation, the first OD is read. At this moment there is no data from the origin, so the estimation comes only from the information that can be taken from the OD. For the first interval of 50 seconds, the estimation is the value of the OD/3. After 50 seconds, an origin data set is created, so for the next estimate (from 50 seconds to 100 seconds), the origin data is taken into account. In this second estimate, we have the OD/3 value as before, but the difference between the estimation of the first interval and the actual value is added; see Eq. 6 for up direction and Eq.7 for down direction. This is used to balance the information. If most passengers from the pattern move in the first interval the second interval and maybe also the third one is consequential. The same will happen if the passengers estimated from the first interval are not as in reality.

$F$ : set of floors

$$Estimation_{up,F} = 0$$

$$Estimation_{down,F} = 0$$

$$Estimation_{up,F} = Estimation_{up,F} + ( OD_{up,F}/3 - Origin_{up,F} ) \quad (6)$$

$$Estimation_{down,F} = Estimation_{down,F} + ( OD_{down,F}/3 - Origin_{down,F} ) \quad (7)$$

## THE MULTIPLE TRAVELLING SALESMAN PROBLEM AND INFORMATION FOR THE OBJECTIVE FUNCTION

Once the passenger flow pattern has been learnt, we need to use it in real time, when the algorithm is taking the decision about which lift should serve each call. If it is assumed that nothing is known about the future, we can estimate the waiting time for the calls assigned to one lift for the MTSP as in Eq. 8, adding the different times needed for the lift to arrive and pick up a passenger waiting for it across different floors, the door close time (DCT), the runtime from the place where the lift was to the passenger's floor, the door open time (DOT) and the transit time (DTT).

$C_l$ : Set of landing calls

$$EWTr = \sum_{C_l}(DCT_{C_l} + runTime_{C_l} + DOT_{C_l} + DTT_{C_l}) \quad (8)$$

If there is some additional information about how many people can be waiting behind this landing call another term can be proposed to estimate this waiting time:

$$EWTP = \sum_{C_l} Estimation_{C_l}(DCT_{C_l} + runTime_{C_l} + DOT_{C_l} + DTT_{C_l}) \quad (9)$$

The estimation of the passengers behind a call is used directly in the MTSP. The MTSP decides the next movement of each lift, how the lifts are going to serve the landing calls. The estimation is used to give more information to the MTSP, making it easier for the MTSP to determine a better route for each lift.

But the final decision of the best route is taken with the objective function. This function can be seen in the Eq. 10.

$$f.Obj = \sum(w1 * EWTr + w2 * EWTP) \quad (10)$$

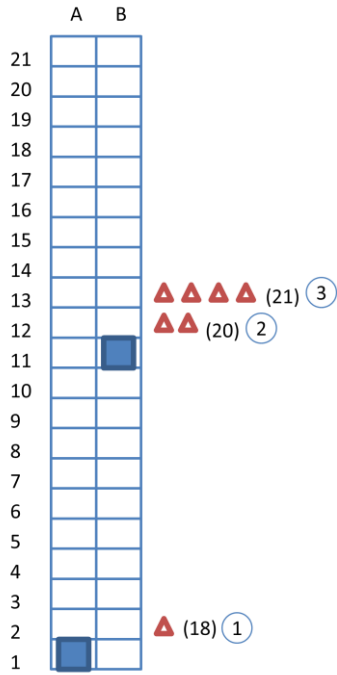
Where EWTr is the expected waiting time of the real landing call, EWTP is the expected waiting time of the probable or the estimated landing calls, and w1, w2 are the weights of the waiting times in the objective function. w1 is for real calls and w2 for the probable or estimated calls. For all the results given in this paper the value used for w1 and w2 is equal to 0.5, giving the same weight to both function objective factors.

In the next example the improvement that can give the estimated data is explained, comparing the same situation with a MTSP with no information of the estimated passengers behind a call and a MTSP with the estimation information.

Fig. 6 shows the building that has been used for this example. The building has 21 floors and two lifts, A and B, with a maximum capacity in each of 5 passengers. There are 3 landing calls. One call on the 2<sup>nd</sup> floor that will go to the 18<sup>th</sup> floor, this call will be the 1<sup>st</sup> one. Then on the 12<sup>th</sup> floor there is another landing call, the 2<sup>nd</sup> one, and in this case it has as destination of the 20<sup>th</sup> floor. And to finish there is a 3<sup>rd</sup> landing call on the 13<sup>th</sup> floor to go to the 21<sup>st</sup> floor.

Behind the 2<sup>nd</sup> call there are 2 passengers waiting, and behind the 3<sup>rd</sup> call there are 4 passengers waiting. This data will be introduced in the MTSP with estimated passenger information.

Fig. 7 shows all the possible options the lifts have to serve the calls. For example, the 3<sup>rd</sup> possibility says that the 1<sup>st</sup> and the 3<sup>rd</sup> calls will be served by lift A and the 2<sup>nd</sup> call by lift B.



n	1	2	3
1	A	A	A
2	A	A	B
3	A	B	A
4	A	B	B
5	B	A	A
6	B	A	B
7	B	B	A
8	B	B	B

Fig. 6 The building used for the example

Fig. 7 All the possible options to attend the calls

Fig. 8 and Fig. 9 show the plans for the lift in every situation, having the passengers' data and not having it. The dark square represent the floor where the landing call has been made, and the light square the destination floor of the passengers.

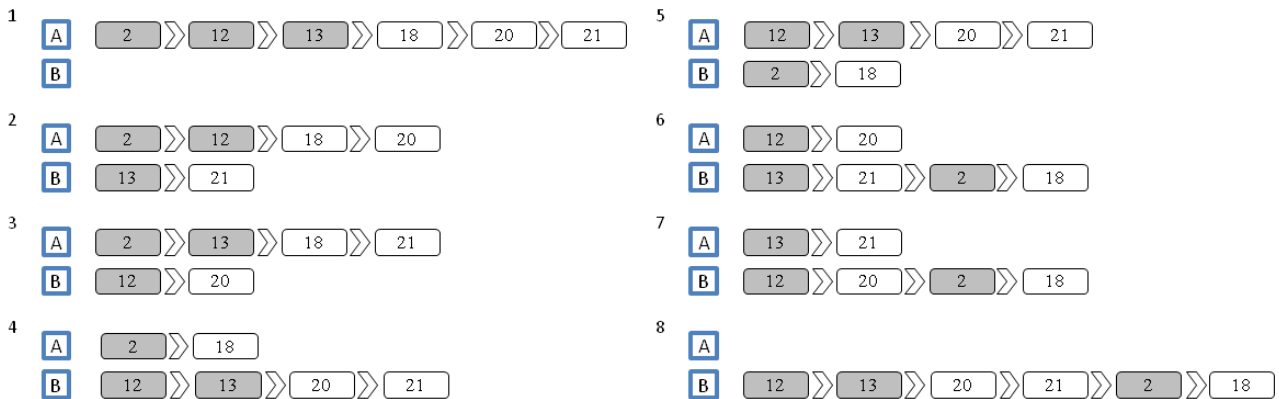
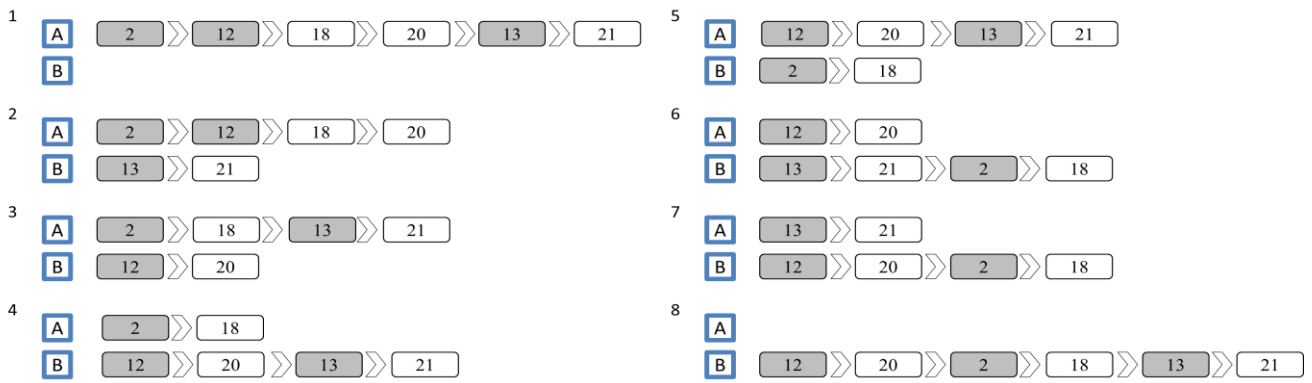


Fig. 8 All the possible plans not having passengers' data





**Fig. 9 All the possible plans having the passengers' data**

In Table 2, the result of the objective function is summarised, highlighting the best plan for both cases, i.e. the plan with least expected waiting time. The winner for the MTSP with no estimated passenger data is the 4<sup>th</sup> plan. The winner for the MTSP with estimate passenger data is the 2<sup>nd</sup> plan.

n	with no data	with data
1	70,9	529,16
2	38,3	118,57
3	38,02	275,04
4	25,6	295,04
5	60,32	403,97
6	90,61	162,23
7	87,45	174,29
8	108,26	656,94

**Table 2 the values of the objective function**

Although the result of the MTSP, 4<sup>th</sup> plan, with no estimated passengers' data appears to win, in reality not all the passengers will be able to enter the lift when it arrives. For example, as the lift capacity is 5 people, when the lift answers the 3<sup>rd</sup> landing call, there is not enough space for all the passengers. So the lift has to return to the 13<sup>th</sup> floor to service the passenger that could enter the first time.

In addition, the result of the MTSP with estimated passenger data penalises the plans where in the first trip the lift cannot serve all the passengers from the same call. This is one of the reasons why the expected waiting time is lower. Also, as there are some estimated passengers, the expected waiting time of those are added in the objective function, thus increasing the value. As the MTSP with the estimated passenger information better manages the capacity of the lift, the best result is different from the MTSP with no data. In this case, the winning plan is the 2<sup>nd</sup> possibility.

## CONCLUSIONS

Passenger flow information can help to improve the estimation of the waiting times, thus benefiting the decisions taken in the dispatching problem. In some of our previous results, even using the simplest application of the methodology explained here, and assuming the system was filling this mixed passenger flow pattern, the benefits in the average waiting time were near 10% and the increment in the car occupancy approximately 20% for the cars at loading levels from 40% to 80%.

The only measure we have noticed that has suffered from all this process is the transit time. We understand that if the lifts have to serve more people, the transit times are longer. Considering an energy aware algorithm [16], the estimation about the number of passengers waiting for the car and their destination will help in finding a better estimation of the energy consumed by each probable route.

Each step of the methodology should be reviewed with the aim of improving these initial results.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Common Misconceptions Regarding Elevator Traffic Simulations

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**Keywords:** Handling Capacity, Elevator Traffic Simulation, Automated Elevator Monitoring Systems, Elevator Speed, Building Traffic Pattern

**Abstract.** Elevator professionals and elevator customers look to both traditional formula based elevator traffic analysis and sophisticated elevator simulation programs to evaluate potential and existing elevator performance with regard to appropriate traffic handling. Sometimes, the terms and concepts involved in such work are misunderstood or misused. This paper discusses five common misconceptions in an attempt to clarify elevating concepts, unify terminology and explain tool limitations.

### INTRODUCTION

Elevator traffic simulations are frequently used by elevator professionals to evaluate proposed elevator configurations for new buildings or existing elevator configurations in standing buildings. In addition to building and elevator characteristics, these simulations require knowledge of the type and rate of elevator passengers as input and rely on specialized software to mimic the performance of elevators under the given input conditions. Elevator simulations can produce many types of output, including passenger wait times and passenger times to destination, that allow the elevator professional to judge whether the elevator configuration can provide acceptable performance in the relevant building.

Observation indicates that many elevator professionals and customers interested in elevator performance, analysis and simulation, do not fully understand the concepts that are used, and misconceptions are common. This paper describes five common misconceptions in an attempt to clarify various terms and situations related to elevating and elevator traffic simulations.

### MISCONCEPTION NUMBER ONE:

**“Handling capacity” is simply how many people are handled by the elevator system in a given amount of time [1, 2, 3, 4].**

Handling capacity calculations have been used as key elevator performance criteria for many years. Traditionally, a handling capacity is a formula based metric and is calculated under very specific performance assumptions. Handling capacity calculations were used to determine how many elevators to put into a new building and to evaluate traffic considerations in existing buildings long before software based elevator simulation programs were available, and they are still used today. Unfortunately, the historical term “handling capacity” has become confused with the newer term “arrival rate”, which is the term applied to the rate of passengers arriving in the elevator lobbies as input to an elevator simulation. Many individuals now use the two terms interchangeably which can be problematic.

Originally, handling capacity referred to the highest percentage of the building population that the elevators could move in a five minute period, on average, given a specific set of building

characteristics (e.g. number of floors in building, height of floors) and elevator characteristics (e.g. speed, size etc. Traditional handling capacity, due to the way it is calculated, is a steady state value meaning that, in theory, the elevator system can serve the calculated volume of traffic for an ongoing period of time. Although the handling capacity produces a steady state value the calculated percentage was usually viewed as the peak capacity of the elevator system, and it was generally concluded that the peak capacity would only be reached for short periods of time each day when numerous passengers all requested elevator service at the same time. Determining the correct number of elevators was based on determining whether the number of elevators being considered could produce the handling capacity needed to move the volume of people during peak elevator traffic.

Elevator traffic simulation studies, which use specially designed software to mimic the performance of elevators in a virtual building, use input data to define how many passengers will request elevator service during the simulation period. The input is determined prior to the simulation execution, unlike traditional handling capacity which is an output, not an input, of the relevant formulas.

If an elevator professional designs a traffic input scenario that has a peak traffic of 10% of the building population then execution of the simulation will output elevator performance metrics (e.g. average wait time) that can be used to determine whether the elevator system could handle a peak traffic of 10%. However, the results will not tell the professional whether 10% is the maximum that the system can handle. If the elevator system can truly only handle a peak of 8% of the population then the simulation results with a traffic input pattern peaking at 10% will indicate that 10% cannot be handled. But, without further studies using different traffic inputs the simulation only reveals that 10% cannot be handled; it does not indicate the actual maximum handling. Similarly, if the simulation results indicate that the elevator system can handle 10% of the population it does not automatically indicate whether it could actually handle more than 10% or how much more than 10%.

It is easy to see why the term handling capacity might be confused with arrival rate because often the goal of defining a handling capacity is to design a system that can handle the peak amount of traffic. So, if a simulation illustrates that the peak traffic expected in a building can be handled by the elevator configuration design an individual may be tempted to call that peak amount of traffic the elevator system's handling capacity. The confusion comes into being when multiple individuals are discussing the same elevator configuration but some are using the term "handling capacity" to mean the maximum handling capacity of a system and others are using it to refer to a rate of traffic expected to arrive at the building. These may not be the same thing. A further point of confusion is whether the expectation is for a calculated handling capacity value or a set of simulation results.

To avoid confusion it is recommended that the term "traditional handling capacity" or "calculated handling capacity" be used to mean the value calculated by probability formulas, the term "maximum handling capacity" be used to indicate the point at which an elevator system can no longer successfully handle additional passengers, and the term "arrival rate" or "demand rate" be used to indicate the flow of passengers used as input to an elevator simulation.

## **MISCONCEPTION NUMBER TWO:**

### **Increasing the elevator speed will provide better service.**

Sometimes increasing the speed of an elevator will provide better service but there are many times when it will not. If an elevator frequently travels through a long express zone, then it is probable that increasing the speed of the elevator will give passengers a faster ride and will take less time to get to waiting hallway passengers. But, if the elevator makes frequent stops at floors near each

other than changing the speed may have little or no impact on the service. This is because when an elevator moves short distances it does not have time to get to full speed. Elevators need to accelerate when leaving a stopped position and decelerate when arriving at the target floor. If the distance between the original and subsequent stops is short, the elevator may need to start decelerating before it has completed the full acceleration phase and reached full speed.

For example, if an elevator travels 4 meters from a stopped position to a stopped position with a motion profile of 2m/sec, 1 m/sec<sup>2</sup> acceleration, and 1.6m/sec<sup>3</sup> jerk then it will take the elevator about 4.5 seconds to move from the first position to the second (assuming no start or machine delays). The highest speed that the elevator will achieve is about 1.4m/sec. If the speed of the elevator is increased to 3m/sec it will still take the elevator about 4.5 seconds to cover the distance and the highest speed it achieves will remain at 1.4m/sec. Therefore, increasing the speed from 2m/sec to 3m/sec offers no performance advantage when the elevator travels short distances.

An elevator that travels 8 meters with a speed of 2m/sec (and other parameters held the same as the previous example) will take 6.4 seconds to travel the distance whereas increasing the speed to 3m/sec would allow the elevator to go from start to stop in 6.1 seconds, a savings of 0.3 seconds. The distance of 8m allows the elevator to achieve full speed, if only for a short time, when using a contract speed of 2m/sec. When using a contract speed of 3m/sec the elevator starts to decelerate when it reaches a top speed of 2.2m/sec and does not reach the full speed of 3m/sec. However, the longer distance of 8 meters is still not sufficient distance to make a difference between elevator speeds if the speeds in question are 7m/sec and 8 m/sec. In this case, neither motion profile would allow the elevator to reach full speed in 8 meters of travel and there would be no performance difference between an elevator traveling 8m at 7m/sec as opposed to one traveling 8m at 8m/sec. As with the 3m/sec case, the elevator traveling at 7m/sec or 8m/sec starts to decelerate once it reaches the speed of 2.2m/sec and does not have enough acceleration time to reach full contract speed.

### **MISCONCEPTION NUMBER THREE:**

**The description of “40-40-20” tells everything one needs to know about elevator traffic input [5].**

Elevator traffic is frequently described by a series of three numbers, the most common of which are “40-40-20” and “45-45-10”. The first number refers to the percent of the passengers that are traveling up from the lobby, the second number refers to the percent of the passengers that are traveling down to the lobby and the third number refers to the percent of passengers that are moving “interfloor” such that neither their origin nor their destination is the lobby. The three numbers must sum to 100%.

This three number shorthand is an excellent way to describe the percentages of each type of elevator traffic, *but it does not indicate the duration or quantity of the traffic*. Therefore, it is easy to misinterpret.

Sometimes, individuals, upon being asked to set up a “40-40-20” traffic simulation scenario, automatically assume that the simulation should use a traffic pattern that moves 40% of the building’s population up from the lobby in one hour, 40% of the building’s population down to the lobby in one hour and 20% of the building’s population from one non-lobby to another non-lobby floor in the course of the same hour. While this might seem to be a good guess, the “40-40-20” actually refers only to the destination percentages of the people being moved and not to whether the distribution is moving all of the building’s population or some percentage of the building’s

population. Neither does “40-40-20” give the time frame over which those people will use the elevators.

In order to accurately depict a traffic distribution to be used for a simulation the “40-40-20” phrase needs to be used in conjunction with a number of people or a percent of the building’s population, together with a time frame. For example, it is appropriate to say “Move 10% of the building’s population in each of five minutes for a 45 minute period using a “40-40-20” configuration” or “Move 550 people evenly over 30 minutes using a “45-45-10” configuration.

The first example means that if you have a building with 1000 people in it then in each of 9 periods of 5 minutes each there will be 100 people attempting to use the elevator (10% of 1000). 40% of those 100 people (i.e. 40 people) will be attempting to travel up from the lobby, 40% of those 100 people (i.e. 40 people) will be attempting to travel down from the lobby and 20% of those people (i.e. 20 people) will be moving interfloor.

The second example means that if you have a building with 1000 people in it then only 55% of the population, or 550 people, will be using the elevator system over 30 minutes. Dividing 550 by 6 (the number of five minute periods in 30 minutes) means that approximately 92 people will desire elevator service in each of those five minutes. Using the “45-45-10” configuration, 45% of those 92 people (i.e. approx. 42 people) want to travel up from the lobby, 45 % (i.e. approx. 42 people) want to travel down to the lobby and the remaining 10% (i.e. approx. 9 people) will be moving interfloor.

#### **MISCONCEPTION NUMBER FOUR:**

##### **Automated elevator monitoring systems are great because they can tell you how long people wait for elevators.**

This misconception applies mainly to automatic systems used to monitor traditional two hall call button elevator configurations.

Automatic elevator monitoring systems can be installed in most modern elevator environments to automatically and routinely collect and tabulate data related to elevator performance. These systems can be very helpful tools, but only if understood and used correctly.

Elevator monitoring systems can only track elements that have a mechanical or electronic component that can transmit information to the computer running the monitoring system. The time that an elevator reaches a floor, the number of buttons that are pressed on a car operating panel, the time and location of an up hall call button being pressed, for example, can all be monitored. The weight of an elevator car can be monitored and, perhaps, used to estimate the number of people in the car. But, with the exception of destination entry systems, in which each passenger indicates their destination with an electronic device, the number of passengers waiting in the hallway for an elevator car is not monitored. Elaborate camera, video, or RFID tracking mechanisms that might allow for passenger tracking are currently too expensive for routine use in elevator performance monitoring.

The result of elevator monitoring limitations is that elevator monitoring systems track elevator response time, the elapsed time between a hall call button being pressed at a floor and the arrival of an elevator to serve the demand at that floor, but cannot track passenger waiting times.

A passenger’s waiting time is the time between the passenger’s arrival in the elevator lobby until the elevator that will serve him or her arrives. It is easy to confuse the elevator response time with

the passenger wait time because in many cases the time value is the same for the elevator and for the person who actually presses the hall call button.

A classic mistake in the use of automated monitoring systems is made when an evaluator looks at the automated monitoring report and sees that the average “wait” time is about 30 seconds and assumes that the elevator service is good. Although most systems report “wait” time, the systems are not really reporting passenger wait times but rather elevator arrival times. Even if the metrics are correctly labeled as response times, many evaluators assume that is the same as wait times. If there is only one passenger waiting then the elevator arrival time (difference between hall call button being activated and elevator arriving at the floor) and the passenger wait time (difference between passenger arriving in hallway and passenger entering elevator) are basically the same thing. However, consider a situation where a first person arrives in the hallway and presses the hall call button and then a second person arrives in the hallway 10 seconds later and then the elevator arrives 20 seconds after that then. The elevator arrival time is 30 seconds, as is the wait time of the first passenger. The second passenger, however, has a wait time of only 20 seconds. The average wait time of these two passengers is 25 seconds, a bit less than the reported “wait” time that is actually the car arrival time of 30 seconds.

The wait time discrepancy described above overstates the actual average wait time and may not be seen as a big problem. The real problem occurs when there is queuing, a situation where not all of the people waiting in the hallway can get into the next arriving car. In this case the elevator arrival times will be reset each time an elevator arrives at the floor, but the actual passenger wait times for those passengers left behind will continue to accrue. This means that the reported “wait” time from an automated monitoring system can seriously under-report wait times during peak elevator traffic when queuing occurs. If the elevator performance is evaluated from the reported wait times under these conditions the evaluation may be significantly incorrect.

#### **MISCONCEPTION NUMBER FIVE:**

**It is easy to figure out a building’s traffic pattern when you have an automated elevator monitoring system.**

It would be great if this were true, but usually it is not. As described in Misconception Number Four, automated monitoring systems are limited in their ability to track individual passengers, especially in conventional two hall call button systems.

In a two button system, it is only the first passenger arriving in the hallway to go a specific direction that presses the hall call button. Therefore, the monitoring system cannot know whether there is one person waiting for the elevator or numerous people waiting. Even after the waiting passengers get into the elevator and press the car call buttons inside the car it is difficult to know how many people entered the car and how many were left behind in the hallway because the car was too crowded. Only the first individual going to a specific floor will be registered as pressing the car call button for that floor and if that button had already been pressed prior to the car’s arrival it will not register another button push. Therefore, the monitoring system has no way to determine precisely how many people entered the elevator or where each of them is going. Arrival rates and passenger specific origin/destinations combinations are key factors of a building’s traffic pattern. Automated monitoring systems, which count hall calls, car calls and car arrival times, and cannot track per passenger arrival times, car entry times or destinations cannot easily produce accurate building traffic patterns.

In a destination entry system it is more likely that the automated monitoring reports will be more correct. This is because in a destination entry system each passenger is expected to use the



destination entry device and the system will be able to monitor each passenger's arrival time, origin floor and destination floor at the entry device. However, it has been consistently observed that in actual practice some people do not enter their destination, relying instead on destinations that have been entered previously or by someone else in their group. Also, some individuals enter their destination multiple times in the hopes of an elevator arriving more quickly and/or a less crowded elevator. In a destination entry system the more people that use the system contrary to its design (i.e. where each passenger enters one and only one destination) the less accurate any traffic pattern determined by monitoring destination entries will be.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## UK's First Urban Cable Car A Project Review of The Emirates Airline

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**Abstract.** The Emirates Air Line is the UK's first urban cable car, it provides a low-emission, quick, direct and fully accessible link across the River Thames, travelling between two new terminals named Emirates Greenwich Peninsula and Emirates Royal Docks. It was completed in June 2012. This review discusses the conception, specification, technical challenges and unique features of this innovative project.

### INTRODUCTION

The Emirates Air Line sits amongst a backdrop of some of London's most famous buildings including Canary Wharf, The Gherkin, Tower 42, The Heron Tower, The BT Tower and the newly completed and iconic building "The Shard". The latter was also constructed by MACE, the same contractor who won the contract to build the Emirates Air Line.

It was erected in advance of the 2012 London Olympic Games and was designed to be a major piece of transport infrastructure for the City as well as having the accolade of being a tourist attraction.

Mayor of London, Boris Johnson said of the project:

*“London’s cable car will boost the on-going renaissance of this easterly quarter of the Capital, helping to secure a massive legacy for Londoners coming from the 2012 Games.”*

In 2013 the Emirates Airline was the winning entry in the Elevator World Project of the Year automated people movers category

The system provides a major new passenger route from the O2 arena (a major London events stadium and the world's largest and busiest music venue) on the south side of the River Thames to the north side just west of the Excel Centre, a major exhibition centre at which the bi annual UK lift exhibition is held. The system makes travel to both venues far easier for persons on the other side of the river.

Both areas surrounding the Emirates Air Line have been earmarked for a number of regeneration projects with the Royal Victoria Docks selected as one of the new Local Enterprise Zones. The Emirates Air Line plays a key role in supporting these regeneration projects by providing a quicker and more direct link. It will also give local communities on both sides of the Emirates Air Line access to a range of entertainment, job and leisure opportunities that are set to become available as regeneration picks up its pace.

### THE BEGINNING OF A CONCEPT

It had been identified that a high density traffic system was needed for moving people from the main Olympic site near Stratford to the equestrian games which were being held on the south side of the river and also that, long term, the expected development of the Canning Town and Silvertown areas of the north bank of the Thames would require better transport links

Analysts considered all options for a transport system including a bridge, water based transport and a tunnel.

Water based transport is comparatively slow and would carry fewer people as the boats have to moor each time to load and unload. There would also need to be a higher operational staff requirement and there would need to be provision for other vessels using the Thames and also the added complication of draft requirements on low tide.

A bridge would have taken a long time to construct and would have required roads to be relocated if vehicles were to use it. A tunnel would have taken even longer.

In April 2011 planning permission was granted to build the first UK Urban Cable Car system which, following sponsorship, acquired the title *The Emirates Airline*

The cable car was selected as the preferred option for a number of reasons including:

- Speed of construction
- Cost
- Traffic handling ability

The project was conceived, designed, installed, tested & commissioned with all the legal compliances required in a matter of 14 months.

### **THE BASE SPECIFICATION**

The system consists of 34 cabins each with the capability of carrying 10 persons. The system can operate at speeds of up to 6 metres per second and at that speed takes 4 minutes and 14 seconds to complete a one way crossing. As a people mover it is capable of transporting 2500 people per hour, a significant number, and forms part of the transport infrastructure of London long after the Olympic Games have left town.

On its first day in operation the system carried over 20,000 people and has proved to be a highly reliable and effective automated people mover. Between opening on June 28<sup>th</sup> and 12<sup>th</sup> August 2012 the system carried over 700,000 people.

The transportation system consists of a continuous single rope measuring 50 mm to which up to 34 cabins can be attached.

An overview of the installation can be seen in *photograph (1)* with a back drop of famous London buildings.



Photograph (1)

Two of the cabins passing with the backdrop of the City of London behind them

The system is incredibly efficient and, as with a traction elevator system, only has to provide power to move the out of balance load when the cabins are out on the line and equally spaced.

The system had to be fully accessible for persons with mobility impairments and the system has a feature that allows cabins to come to a stand for loading and unloading whereas in normal operation the cabins keep moving at a slow pace in the station areas. In order to achieve this feature an anti-collision system had to be designed into the software to prevent cabins coming into contact with each other.

## **TECHNICAL CHALLENGES & UNIQUE FEATURES**

The project had huge technical challenges as well as having enormous public expectations and high profile stakeholders (including the Mayor of London). During the Olympics the system was used by the public and the athletes to access the equestrian games which were being held on the south side of the river in Greenwich and the Excel centre where the boxing events were held.

The unique aspects of the project have called for some innovative construction techniques and a number of firsts in the industry, for example the erection of the South Tower called for the installation of the largest lifting capacity crawler crane in Europe. The crawler crane, which runs on tracks and not wheels to aid mobility, was put together, on-site, over a period of two weeks and delivered using more than 70 articulated lorries. When assembled, its reach was 120 metres with a height of 183 metres. The huge temporary structure dubbed LR 1350 had a maximum lifting capacity of 1,350 tonnes - the equivalent of 193 Routemaster buses. The immense lift capacity was required to lift the huge pieces of each tower section into place, weighing up to 68 tonnes each.

The Emirates Air Line has also achieved another first – appearing on the London Underground Tube map. It is the first time in the Tube map's 78 year history that a commercial brand has been able to put their name to a transport link and station as a result of a partnership with Transport for London (TfL). The map highlights how the new scheme will integrate into the wider transport network by providing an additional step free access interchange between the Jubilee line and the Docklands Light Railway (DLR) - two key lines in east London.

The project team was immediately faced with some big challenges, the first being how they were going to construct the two main towers (both 86m tall and weighing 570 tonnes) to accommodate the river crossing and one smaller intermediate tower which measures over 65 metres in height and weighs 270 tonnes.

It is not only the size of the towers, and the fact that one had to be positioned in the River Thames, which made the construction so challenging, but also the need for exacting stability as a core requirement for the operation of the cable car. The design of the towers, using a complex helix structure to link the four steel ribbons assisted in providing this stability. The towers, made up of approximately 6,500 pieces of steel of varying thicknesses from 30 – 50mm ribbons shaped then welded together before being connected to helix tubes that run inside the tower and provide the required stiffness. The huge crane used to construct the south tower can be seen in *photograph (2)*.



Photograph (2)

The huge crane that was required for the construction of the towers

There are three main towers and two compression towers. The main towers support the system at height and the compression towers provide rope diversion from the stations to the head of the towers.

The towers were designed specifically for the project by an architect and structural engineers. The south tower can be seen in *photograph (3)* during construction along with the roller batteries waiting lifting onto the tower in *photograph (4)*.



Photograph (3)

The south tower post construction before the stringing\* took place

\*The cable car world call “roping” the installation “stringing!”



Photograph (4)

The south tower roller batteries on the floor prior to lifting onto the tower head

Three towers have been provided due to one of the engineering challenges being the need for a 51 metre tall ship to be able to pass under the system at high tide! The tide can vary up to 3.76 metres during its twice daily phase. HMS Ocean, one of the UK's largest warships, is the largest vessel that has been under the installation having been in London to provide security during the Olympic Games.

The only way the line could be maintained at a height to meet the tall ship criteria was by introducing a third tower. The towers are 86 metres tall and their baby sister (the north intermediate tower) is 65 metres.

Another challenge faced by the project team was how it was going to pull the cable between the terminals via the towers over the Royal Victoria dock and the River Thames. This has constituted a highly complex and intricate part of the construction of the landmark project.

Each tower has been topped with a Doppelmayr 'head' (named after specialist cable car contractor Doppelmayr) which allows the cabling to run across the tops of the structures. The cable, made of twisted steel comprised of 300 separate strands of steel and is 50mm thick, stretches 1.1km across the river. Boats were used to make the initial rope connection during the short night time window when the tide was at its lowest, working with the Port of London Authority to keep the river clear, and this was eventually replaced with the cable itself. The cable was pulled into place and tensioned using a 12-tonne winch located on the platform of the South Terminal (Emirates Greenwich Peninsula). The cable was clamped and secured at each terminal and tensioned to gain a minimum clearance of 54m above the mean high watermark.

The system has a traction sheave and a return pulley/diverter sheave (bull wheel) which is tensioned in a similar fashion to an escalator step chain. The return pulley/diverter sheave (bull wheel) can be seen in *photograph (5)*



Photograph (5)  
The main “bull wheel”\* and tensioning system in the south station.

\*The cable car world call “diverters” by the name “bull wheels”. The bull wheel is large as it acts as a spanning sheave setting the width apart that the lines run

Once the cable had been tensioned to the correct height, the next step was to carry out the rigorous testing and commissioning process for the whole system.

Another engineering challenge faced by the team was the fact that we had to be wary of the flight path into the nearby London City Airport. The lower end of the emergency approach into the airport is 110 metres only 23 metres above the top of the south tower.

The designers also had to be aware of the potential for an out of control vessel to strike a tower causing damage to the system and potential risks. Whilst the risk was assessed as incredibly low a ship impact system has been employed to divert any risk away from the towers. The south tower has been constructed in the main river itself which again presented challenges.

The construction programme was another challenge faced by the team. Construction started in July 2011 and the completed project was handed over on June 28<sup>th</sup> 2012 a little over 10 months. This is an incredible achievement given the design and constructions issues that the team faced.

After the design stage construction issues also had to be faced!

The UK has had its worst period of inclement weather since records began! It has, on most days, been pouring down with rain and there was also a period of snow!

One of the major time consuming construction issues was the fact that the bed of the River Thames was found to be unstable. Whilst this was no surprise given the exploits of Isambard Kingdom Brunel when he was building the East London Foot Tunnel in the early 1800's in discovering that this was the case it wasn't anticipated that the problem would be some 30 metres deeper than expected!

Nevertheless the project was completed before the start of the Olympic Games. The newly delivered cabins still in their protective coverings can be seen in *photograph (6)*



Photograph (6)

The new cabins in the garaging section at the south station with their protective coverings awaiting their inaugural run over the Thames

Another challenging issue was designing the system such that all passengers could be retrieved from the system in a timely manner in the event of failure. The design is such that there is a huge amount of redundancy and system support including an innovative emergency bearing system which has been incorporated in case of a bearing failure on the main traction and tensioning sheaves. The bearing design was developed specifically for this project and is the first time that it has been used although the success of the design means that it will be adopted on future cable car projects around the world.

## OPENING DAY

A truly magnificent piece of infrastructure that will provide London with an aesthetically pleasing way of moving significant numbers of people for years to come. It is understood that on Saturday 11<sup>th</sup> August the system moved over 32,000 passengers in one day and we feel it is worthy of recognition.

Following the rigorous testing process, the Emirates Air Line was opened by the Mayor of London, Boris Johnson on 28 June 2012 – one month before the Olympic Games opening ceremony and just 12 months since construction commenced on site. The system is fully accessible to passengers in wheelchairs or with bikes, as well as parents with children in pushchairs. Our first wheelchair bound passenger can be seen in *photograph (7)*.



Photograph (7)

The first mobility impaired passenger using the system



# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Modeling and simulation of a high-rise elevator system to predict the dynamic interactions between its components

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**Abstract.** Lateral vibrations of suspension and compensating ropes in a high-rise elevator system are induced by the building motions. When the frequency of the building coincides with the fundamental natural frequency of the ropes, large resonance whirling motions of the ropes result. This phenomenon leads to impacts of the ropes the elevator walls, making the building and elevator system unsafe. The impact loads affect the performance of the elevator installation resulting in interruptions of service and damage to the components of the system. Furthermore, the car, counterweight and compensating sheave suffer from vertical vibrations due to the coupling with the lateral vibrations of the ropes. This paper presents a comprehensive mathematical model of a high-rise elevator system taking into account a scenario when the car is parked at the landing level corresponding to the resonance length of the ropes. The model is implemented in a high performance computational environment and the dynamic response of the system when the building is subject to a low frequency sway, is determined through numerical simulation. The results predict a range of nonlinear dynamic interactions between the components of the elevator system that play a significant role in the operation of the entire installation.

## INTRODUCTION

Lateral vibrations of the suspension and compensating ropes in a high-rise elevator system are induced by the building motions caused by high winds in the in-plane and the out of plane directions. When one of the two fundamental frequencies of the building coincides with one of the natural frequencies of the ropes, large resonance whirling motions of the ropes result. This phenomenon results in impact loads in the elevator shaft, leading to adverse dynamic behavior of the elevator system. The impact loads affect the elevator installation resulting in interruptions of service and damage to the components of the system. Furthermore, the car, counterweight and compensating sheave suffer from vertical vibrations due to the coupling with lateral vibrations of the ropes.

The behaviour of a suspension rope – elevator car system was studied in [1,2]. The study involved a suspension rope of time-varying length with a mass representing an elevator car traveling according to a prescribed velocity and acceleration time-profiles. The excitation was implemented through harmonic motions applied at the top of the hoist structure. Autoparametric nonlinear nonstationary resonance phenomena were then investigated through a range of numerical simulation test.

This paper presents a comprehensive mathematical model of a high-rise stationary elevator system taking into account a scenario when the car is parked at the landing level corresponding to the resonance length of the compensating ropes. The model is implemented in the MATLAB computational environment and the dynamic response of the system when the building is subjected to a low frequency sway in both lateral in-plane and lateral out-plane, is determined using numerical simulation techniques. The results predict a range of nonlinear dynamic interactions between the

components of the elevator system that play a significant role in the operation of the entire installation.

## DESCRIPTION OF THE MODEL OF AN ELEVATOR SYSTEM

The elevator ropes are flexible and have low internal damping. Therefore, at resonance conditions they often vibrate at large amplitudes.

The model of an elevator system with a car of mass  $M_1$ , compensating sheave of mass  $M_2$ , and counterweight of mass  $M_3$ , is depicted in Fig. 1. The suspension and compensating ropes have mass per unit length  $m_1$  and  $m_2$ , elastic modulus  $E_1$  and  $E_2$ , and effective cross-section are  $A_1$  and  $A_2$ , respectively. The parameter  $b_1$  represents the distance measured from the bottom landing level to the center of the compensating sheave. The parameter  $b_2$  denotes the distance measured from the center of the traction sheave to the center of the diverter pulley and  $h_0$  represents the distance measured from the bottom landing level to the center of the traction sheave. The parameter  $h_{trav}$  is the height of travel of the elevator car. The parameter  $h_{car}$  is the height of the car. The parameter  $h_{cw}$  is the height of the counterweight. The parameter  $h_t$  is the position of the elevator car measured from the bottom landing level to the bottom of the elevator car.

The lengths of the suspension rope and of the compensating rope are defined as follows. The length of the suspension rope at the car side measured from the center of the traction sheave to the termination at the car crosshead beam is denoted by  $L_1$ . The length of the compensating rope at the car side measured from the termination at the car bottom to the center of the compensating sheave is denoted as  $L_2$ . The length of the compensating rope at the counterweight side measured from the termination at the counterweight to the center of the compensating sheave is denoted by  $L_3$ . The length of the suspension rope at the counterweight side measured from the center of the diverter pulley to the termination at the counterweight end is denoted by  $L_4$ . The mass moment of inertia of the diverter pulley and the short stretch of the suspension rope between the pulley and the traction sheave is neglected in the simulation model.

The response of the elevator ropes subjected to dynamic loading due to the building sway are represented by the lateral in-plane and lateral out of plane displacements denoted as  $V_i(x_i, t)$  and  $W_i(x_i, t)$  where the subscript  $i=1,2,3,4$  corresponds to the sections of the ropes of length  $L_1$ ,  $L_2$ ,  $L_3$ , and  $L_4$ , respectively. The lateral in-plane and lateral out of plane motions of the ropes are coupled with the longitudinal motions of the ropes that are denoted as  $U_i(x_i, t)$ . The longitudinal motions of the car, compensating sheave and counterweight are denoted as  $U_{CR}(t)$ ,  $U_{CS}(t)$ , and  $U_{CW}(t)$ , respectively.

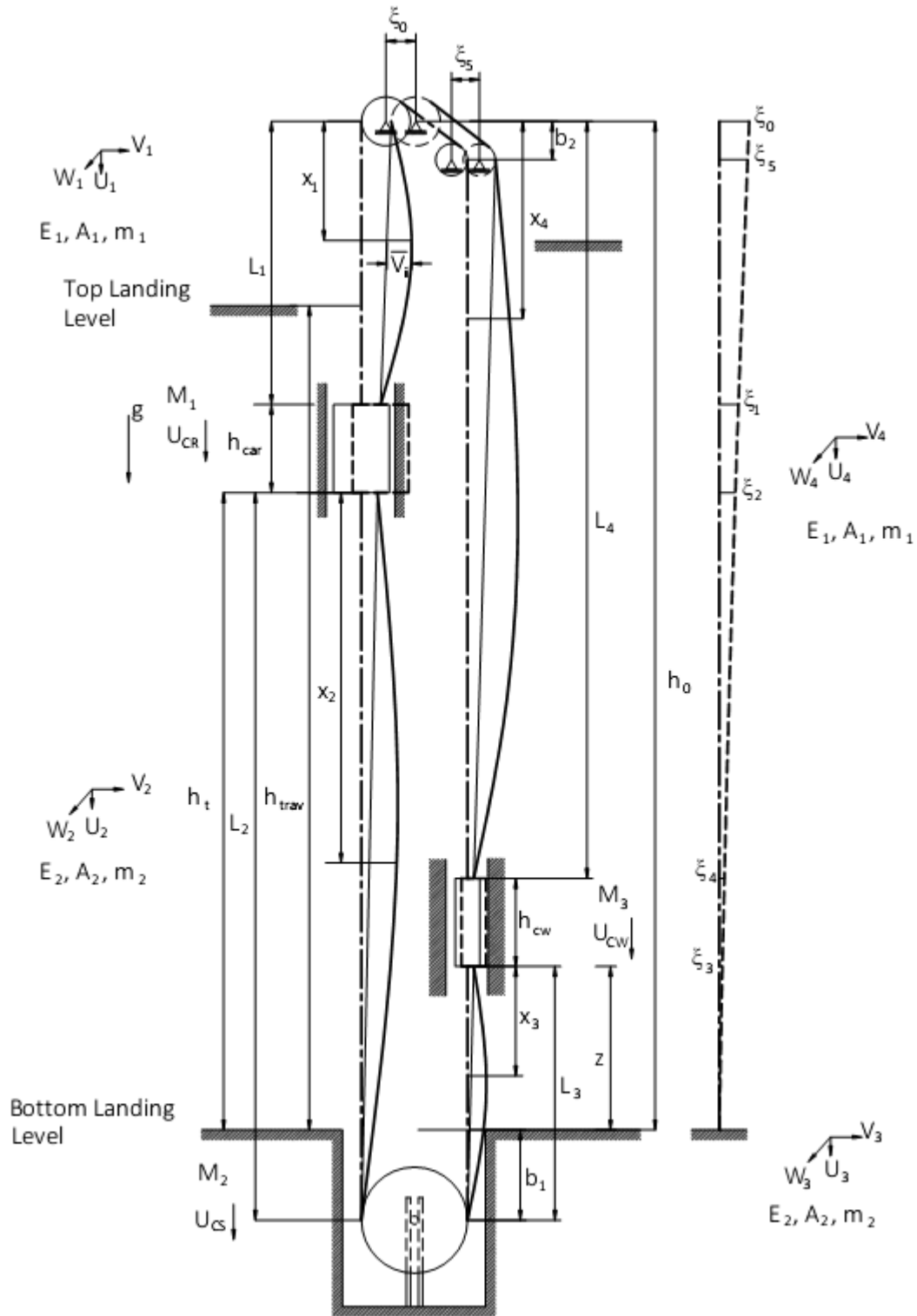


Figure 1. Elevator system.

The building structure is subjected to bending deformations in the in-plane and out of plane directions, described by the shape function  $\Psi(z)$ , with  $z$  denoting a coordinate measured from the bottom landing level. The bending deformations result in harmonic motions  $C_v(t)$  and  $C_w(t)$  of frequency  $\Omega_v$  and  $\Omega_w$  and amplitude  $A_v$  and  $A_w$  in the lateral in-plane and lateral out of plane directions, respectively.

## VIBRATION MODEL

The mean tensions of each stretch of the ropes are expressed as

$$T_1(x_1) = M_1g + m_1g(L_1 - x_1) + m_2gL_2 + \frac{M_2g}{2}. \quad (1)$$

$$T_2(x_2) = \frac{M_2g}{2} + m_2g(L_2 - x_2). \quad (2)$$

$$T_3(x_3) = \frac{M_2g}{2} + m_2g(L_3 - x_3). \quad (3)$$

$$T_4(x_4) = M_3g + m_1g(L_4 - x_4) + m_2gL_3 + \frac{M_2g}{2}. \quad (4)$$

where  $g$  is the acceleration of gravity and  $x_i$  represent the spatial coordinate corresponding to the sections of the ropes of length  $L_1$ ,  $L_2$ ,  $L_3$ , and  $L_4$ , respectively. The axial Green's strain measure representing stretching of the rope section  $i$  is given as

$$\varepsilon_i = U_{ix} + \frac{1}{2}(V_{ix}^2 + W_{ix}^2). \quad (5)$$

where  $(\ )_x \equiv \frac{\partial(\ )}{\partial x}$ . The equations governing the undamped dynamic displacements  $U_i(x_i, t)$ ,  $V_i(x_i, t)$ ,  $W_i(x_i, t)$ ,  $U_{CR}(t)$ ,  $U_{CS}(t)$ , and  $U_{CW}(t)$  can be developed by applying Hamilton's principle, which yields

$$m_i V_{iit} - T_{ix} V_{ix} - E_j A_j \varepsilon_{ix} V_{ix} - T_i V_{ixx} - E_j A_j \varepsilon_i V_{ixx} = 0. \quad (6)$$

$$m_i W_{iit} - T_{ix} W_{ix} - E_j A_j \varepsilon_{ix} W_{ix} - T_i W_{ixx} - E_j A_j \varepsilon_i W_{ixx} = 0. \quad (7)$$

$$m_i U_{iit} - E_j A_j \varepsilon_{ix} = 0. \quad (8)$$

$$M_1 \ddot{U}_{CR} - M_1 g + T_1(L_1) + E_1 A_1 (\varepsilon_1) \Big|_{x=L_1} - T_2(0) - E_2 A_2 (\varepsilon_2) \Big|_{x=0} = 0. \quad (9)$$

$$M_2 \ddot{U}_{CS} - M_2 g + T_2(L_2) + E_2 A_2 (\varepsilon_2) \Big|_{x=L_2} + T_3(L_3) + E_2 A_2 (\varepsilon_3) \Big|_{x=L_3} = 0. \quad (10)$$

$$M_3 \ddot{U}_{CW} - M_3 g + T_4(L_4) + E_4 A_4 (\varepsilon_4) \Big|_{x=L_4} - T_3(0) - E_2 A_2 (\varepsilon_3) \Big|_{x=0} = 0. \quad (11)$$

where  $(\ )_t \equiv \frac{\partial(\ )}{\partial t}$  and an overdot denotes the derivative with respect to time.

According to [3], in high rise buildings the bending motion frequencies  $\Omega_v$  and  $\Omega_w$  are much smaller than the longitudinal frequencies of the ropes, and we can assume that no interaction will take place between the lateral modes and the longitudinal modes of the ropes. As a result, the longitudinal inertia of all ropes can be neglected in Eq. (8) so that the model is reduced to two equations for each section of the suspension and compensating rope, respectively.

The boundary conditions in the lateral in-plane direction are defined as

$$V_1(0, t) = \xi_0(t). \quad V_1(L_1, t) = \xi_1(t). \quad (12)$$

$$V_2(0, t) = \xi_2(t). \quad V_2(L_2, t) = 0. \quad (13)$$

$$V_3(0,t) = \xi_3(t). \quad V_3(L_3,t) = 0. \quad (14)$$

$$V_4(0,t) = \xi_5(t). \quad V_4(L_4,t) = \xi_4(t). \quad (15)$$

Where  $\xi_0(t)$ ,  $\xi_1(t)$ ,  $\xi_2(t)$ ,  $\xi_3(t)$ ,  $\xi_4(t)$ , and  $\xi_5(t)$  represent the lateral displacements of the structure corresponding to the top of the structure and to the position of the car and counterweight (see Fig. 1). Similarly, the lateral out-plane displacements at the boundaries can be defined in a similar way. In order to accommodate the excitation in the equations of motion Eq. 6 and Eq. 7 the overall lateral in-plane displacements of each rope is expressed as

$$V_1(x_1,t) = \bar{V}_1(x_1,t) + \left(1 + (\psi_1 - 1) \left(\frac{x_1}{L_1}\right)\right) C_v(t). \quad 0 < x_1 < L_1. \quad (16)$$

$$V_2(x_2,t) = \bar{V}_2(x_2,t) + \left(1 - \frac{x_2}{L_2}\right) \psi_2 C_v(t). \quad 0 < x_2 < L_2. \quad (17)$$

$$V_3(x_3,t) = \bar{V}_3(x_3,t) + \left(1 - \frac{x_3}{L_3}\right) \psi_3 C_v(t). \quad 0 < x_3 < L_3. \quad (18)$$

$$V_4(x_4,t) = \bar{V}_4(x_4,t) + \left(\psi_5 + (\psi_4 - \psi_5) \left(\frac{x_4}{L_4}\right)\right) C_v(t). \quad 0 < x_4 < L_4. \quad (19)$$

where  $\bar{V}_i(x_i,t)$  are the displacements of the rope relative to the configuration each rope when it is stretched by the structure motion. Furthermore,  $\psi_1$ ,  $\psi_2$ ,  $\psi_3$ ,  $\psi_4$ , and  $\psi_5$  are the deformations obtained from the shape function  $\Psi(z)$  which is assumed to be related to the fundamental mode of the high rise building and is approximated by a cubic polynomial as follows:

$$\psi_1 = 3 \left(1 - \frac{L_1}{h_0}\right)^2 - 2 \left(1 - \frac{L_1}{h_0}\right)^3. \quad (20)$$

$$\psi_2 = 3 \left(\frac{L_2 - b_1}{h_0}\right)^2 - 2 \left(\frac{L_1 - b_1}{h_0}\right)^3. \quad (21)$$

$$\psi_3 = 3 \left(\frac{L_3 - b_1}{h_0}\right)^2 - 2 \left(\frac{L_3 - b_1}{h_0}\right)^3. \quad (22)$$

$$\psi_4 = 3 \left(1 - \frac{L_4 - b_2}{h_0}\right)^2 - 2 \left(1 - \frac{L_4 - b_2}{h_0}\right)^3. \quad (23)$$

$$\psi_5 = 3 \left(1 - \frac{b_2}{h_0}\right)^2 - 2 \left(1 - \frac{b_2}{h_0}\right)^3. \quad (24)$$

Similarly, the lateral out-plane displacements of each rope are expressed in the same way. Using the transformations from Eq. (16) to Eq. (19) in Eq. (6) for the lateral in-plane motion, an approximate solution to the nonlinear partial differential equation of motion is determined by using the Galerkin method with the following finite series:

$$\bar{V}_i(x_i,t) = \sum_{r=1}^N \phi_{ir}(x_i) q_{ir}(t). \quad (25)$$

$$\bar{W}_i(x_i,t) = \sum_{r=1}^N \phi_{ir}(x_i) z_{ir}(t). \quad (26)$$

where  $\phi_{ir}(x_i) = \sin\left(\frac{n\pi}{L_i} x_i\right)$ ;  $r = 1, 2, 3, \dots, N$ ; with  $N$  denoting the number of modes, are the natural vibration modes of the corresponding  $i^{th}$  rope and  $q_{ir}(t)$  and  $z_{ir}(t)$ ;  $r = 1, 2, \dots, N$  represent the lateral in-plane and lateral out of plane modal displacements, respectively.

These results in the following set of 4xN ordinary differential equations

$$\ddot{q}_{ir}(t) + 2\zeta_{ir}\omega_{ir}\dot{q}_{ir}(t) + \sum_{p=1}^N \bar{K}_{irp} q_{ip}(t) = \bar{f}_{ir}^q + N_{ir} q_{ir}(t). \quad (27)$$

$$\ddot{z}_{ir}(t) + 2\zeta_{ir}\omega_{ir}\dot{z}_{ir}(t) + \sum_{p=1}^N \bar{K}_{irp} z_{ip}(t) = \bar{f}_{ir}^z + N_{ir} z_{ir}(t). \quad (28)$$

The modal damping represented by the ratios  $\zeta_{ir}$  and the undamped time varying natural frequencies of the element  $\omega_{ir}$ . The  $\bar{K}_{irp}$  is the stiffness matrix,  $\bar{f}_{ir}^q$  and  $\bar{f}_{ir}^z$  represent the excitation force terms and  $N_{ir}$  are the nonlinear terms.

Similarly, the equations of motion for the car, compensating sheave, and counterweight from (9) to (11) are transformed into the modal coordinates using the transformation

$$\vec{U} = [Y] \vec{S} \quad (29)$$

where  $\vec{U} = [U_{CR} \ U_{CS} \ U_{CW}]^T$  and  $\vec{S} = [S_{CR} \ S_{CS} \ S_{CW}]^T$  is a vector of modal-coordinates corresponding to the system comprising the car, compensating sheave, and counterweight, respectively. If  $[Y]$  is the mass-normalized mode shape matrix, the following set of equations describing the vertical response of the car, compensating sheave and counterweight: in terms of the modal parameters

$$\ddot{S}_{CR}(t) + 2\zeta_{CR}\omega_{CR}\dot{S}_{CR}(t) + \omega_{CR}^2 S_{CR}(t) = (\vec{Y}^{(1)})^T (\vec{F} + \vec{\eta}). \quad (30)$$

$$\ddot{S}_{CS}(t) + 2\zeta_{CS}\omega_{CS}\dot{S}_{CS}(t) + \omega_{CS}^2 S_{CS}(t) = (\vec{Y}^{(2)})^T (\vec{F} + \vec{\eta}). \quad (31)$$

$$\ddot{S}_{CW}(t) + 2\zeta_{CW}\omega_{CW}\dot{S}_{CW}(t) + \omega_{CW}^2 S_{CW}(t) = (\vec{Y}^{(3)})^T (\vec{F} + \vec{\eta}). \quad (32)$$

where  $\zeta_{CR}$ ,  $\zeta_{CS}$ ,  $\zeta_{CW}$  and  $\omega_{CR}$ ,  $\omega_{CS}$ ,  $\omega_{CW}$  denote the modal damping ratios and the natural frequencies of the car, compensating sheave and counterweight, respectively, and  $\vec{Y}^{(i)}$  is the  $i$ th

mode shape vector. The  $\vec{F} = \begin{bmatrix} \bar{F}_{CR} \\ \bar{F}_{CS} \\ \bar{F}_{CW} \end{bmatrix}$  is the excitation vector, and the  $\vec{\eta} = \begin{bmatrix} \eta_{CR} \\ \eta_{CS} \\ \eta_{CW} \end{bmatrix}$  is a vector with

components representing the nonlinear couplings with the lateral motions of the ropes.

## CASE STUDY

The dynamic performance of an elevator system comprising seven ( $n_1 = 7$ ) steel wire suspension ropes and four ( $n_2 = 4$ ) steel wire compensating ropes of mass per unit length  $m_1 = 0.723$  kg/m and  $m_2 = 1.1$  kg/m, having modulus of elasticity  $E = 54535$  N/mm<sup>2</sup> and nominal diameters  $d_1 = 13$  mm and  $d_2 = 16$  mm, respectively. The modal damping ratios for the ropes are assumed as 0.3% across all modes and 10% for the lumped mass across all modes. The height measured from the ground floor level to the center of the traction sheave is  $h_0 = 88.875$  m, the car and counterweight height is

$h_{cw} = h_{car} = 4.00$  m, travel height  $h_{trav} = 80.70$  m, the car mass with full load is  $M_1 = 4400$  kg, the mass of the compensating sheave is  $M_2 = 600$  kg, and the mass of the counterweight is  $M_3 = 3600$  kg. The elevator car is positioned at the top landing level. The height measured from the bottom landing level to the center of the compensating sheave is given as  $b_1 = 2.02$  m and the height from center of the traction sheave to the center of the diverter pulley is  $b_2 = 0.80$  m. The high rise building is excited by the wind harmonically in the lateral in-plane direction with a frequency of  $\Omega_v = 1.220$  rad/s (0.1941 Hz), amplitude of  $A_v = 0.07$  m and in the lateral out of plane direction with a frequency of  $\Omega_w = 0.314$  rad/s (0.05 Hz) and amplitude of  $A_w = 0.005$  m. Table 1 shows the frequencies of the first 4 modes of the ropes.

Rope No. #	1 Mode [Hz]	2 Mode [Hz]	3 Mode [Hz]	4 Mode [Hz]
1	11.88	23.76	35.63	47.51
2	0.19	0.39	0.58	0.80
3	6.45	12.89	19.35	25.80
4	0.53	1.06	1.60	2.13

Table 1. The first 4 natural frequencies of the ropes.

The variation of the first four natural frequencies of the compensating ropes at the car side against the position of the elevator car in the hoistway measured from the bottom landing level is shown in Fig. 2. The horizontal lines represent the lateral in-plane and the lateral out of plane frequencies of the building.

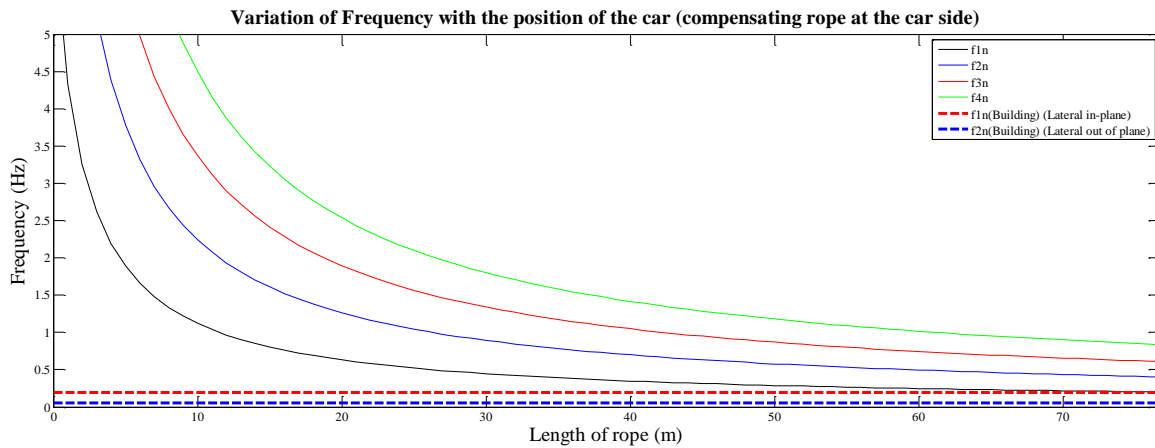


Figure 2. Variation of the first four natural frequencies of the compensating ropes at the car side.

The trajectory of the building recorded at the machine room level over time interval of 60 seconds is shown in Fig. 3.

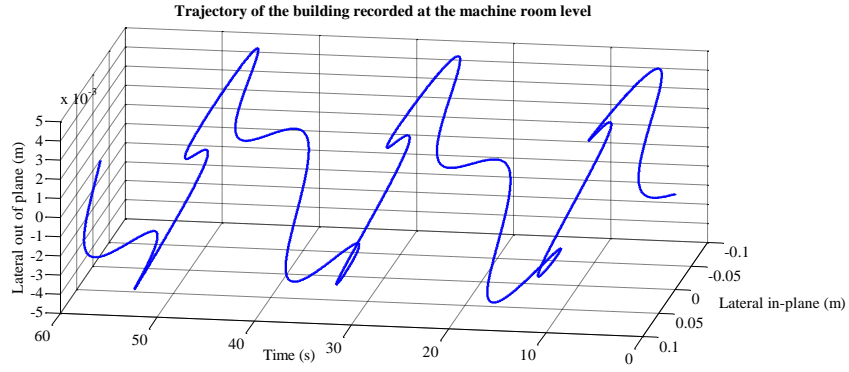


Figure 3. Trajectory of the building recorded at the machine room level.

The mode shapes corresponding to the vertical vibrations of the car, compensating sheave and counterweight are shown in Fig. 4 (a), (b) and (c), respectively. In the first mode (2.58 Hz) the compensating sheave and counterweight have greater displacements than the car and they are in phase. The second mode (8.54 Hz) is dominated by the car motion with the displacements of the compensating sheave and counterweight being almost zero. In the third mode (33 Hz) the car motions are negligible and the compensating sheave vibrations are dominant. The displacements of the compensating sheave and counterweight are out of phase.

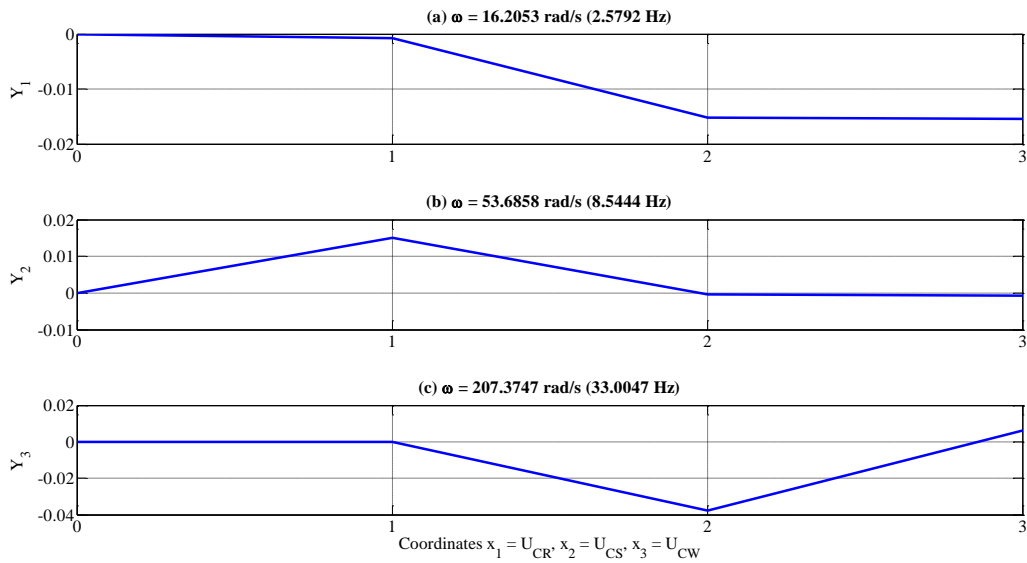


Figure 4. The mode shape displacements of the car, compensating sheave and counterweight.

In order to predict the dynamic response of the ropes and discrete masses, the equations of motion Eqs. (27), (28), (30), (31), and (32) are integrated numerically using an explicit Runge-Kutta fourth- and fifth-order formula. The numerical procedure is started from the initial instant  $t_0 = 0$  s until  $t_f = 600$  s.

The lateral in-plane and the lateral out of plane displacements versus time are shown in Fig. 5 (a) and (b), respectively. The displacements in the lateral out of plane directions are very small when the simulation starts. However, they are increasing with time and whirling motions of the rope result as shown in Fig. 6.



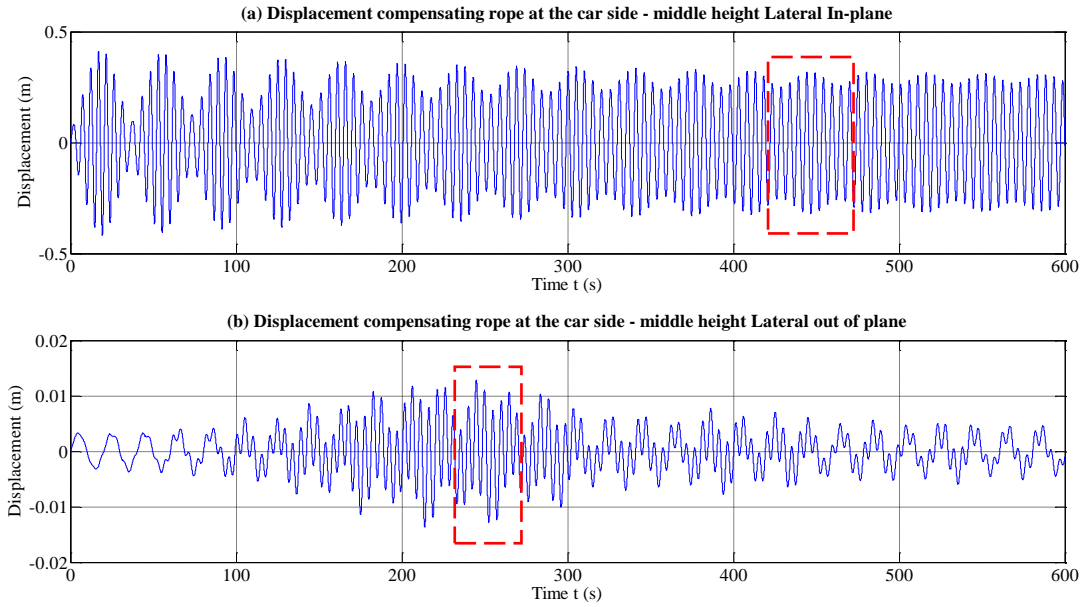


Figure 5. The mid-span displacements of the compensating rope at the car side with respect to time.

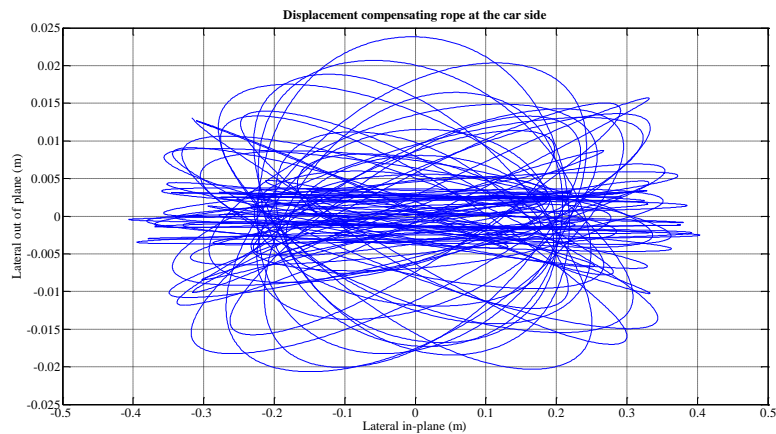


Figure 6. Lateral displacement of the compensating ropes at the car side.

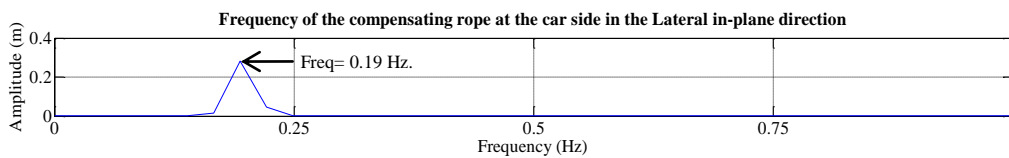


Figure 7. Frequency of the compensating rope at the car side in the Lateral in-plane.

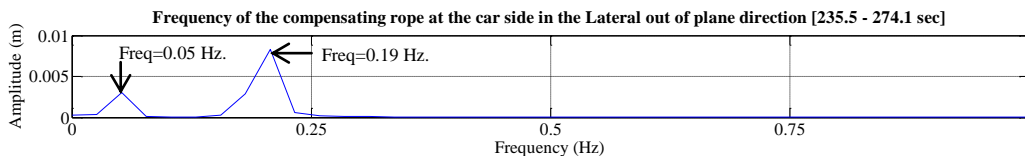


Figure 8. Frequency of the compensating rope at the car side in the Lateral out of plane.

The displacement time records of the car, compensating sheave, and counterweight are shown in Fig. 9 (a), (b), and (c), respectively, with the corresponding frequency spectra plotted in Fig. 9 (d), (e), and (f), respectively. It is evident that the dominant frequency is twice the frequency of the in-plane excitation (0.39 Hz). The FFT frequency spectra of the lateral in-plane over a time span of 428.8 – 464.9 s and for the lateral out of plane directions over a time span of 235.5 – 274.1 s are

shown in Fig. 7 and 8, respectively. It is evident that the dominant frequency is the frequency of the in-plane direction (0.19 Hz).

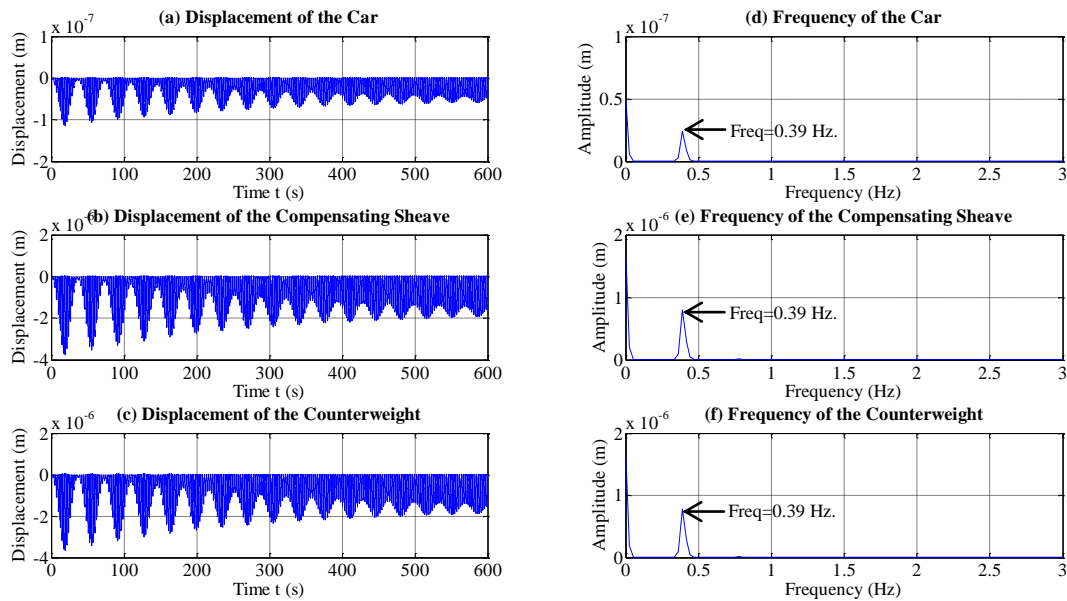


Figure 9. Displacements and FFT frequency spectra of the car, compensating sheave, and counterweight.

## CONCLUSIONS

The equations of motion of a stationary elevator system comprising an elevator car, compensating sheave, counterweight, with suspension and compensating ropes excited by the high rise building motions are derived in this paper. These equations accommodate the nonlinear effects of the rope stretching in the lateral in-plane and the lateral out of plane directions. This model is used to predict the response of the system. Numerical simulation results show that at the resonance conditions the transfer of energy from the lateral in-plane mode to the lateral out of plane mode takes place. While the motions of the structure are small, the rope is experiencing large lateral whirling motions. If the response of the ropes continue to grow impact phenomena in the hoistway might occur which may lead to excessive vibrations of the car and damage to the system components.

## ACKNOWLEDGMENTS

Support received from ThyssenKrupp Elevator AG for the research work reported in this paper is gratefully acknowledged.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Lift design for modern buildings: What is the market looking for?

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**Abstract.** This paper sets out to look at lift design from a building marketing perspective and to explore how BCO 2009 has changed the understanding of letting agents, tenants and designers as to what is expected from modern lift design. The publication of BCO 2009 has fundamentally changed the way lift performance is viewed by sales and marketing organisations. The introduction of terms such as Average Waiting Time and Time to Destination are far more tangible than Handling Capacity and Interval. In addition the recognition of higher density levels and the use of simulation moves lift design to a new level which feeds through to the marketing of buildings.

### BACKGROUND

Prior to the publication of BCO 2009 [1], CIBSE Guide D [2] was used as the key reference document for lift traffic analysis. The 15% handling capacity and 30 second interval were the benchmark criteria used to assess and design lift systems for the modern office buildings of their era. Along with the performance criteria the CIBSE Guide D of the day also provided advice related to population density levels for varying types of office accommodation. For prestigious offices a density of one person to 14m<sup>2</sup> was detailed, and became the commonly used figure by many consultants and designers in their calculations. Having calculated the total population it was acceptable to apply a discount for absence.

Whilst this approach provided the basis for lift design for a considerable period, changes were taking place in the way buildings were being used. Office buildings were increasingly seen by tenants and owners as an asset that had to 'earn its keep'. The method employed to do this was to simply pack in more people. The impact of this obviously has implications beyond the ability of the lifts to handle the extra population, but this was seen as a means of making the building 'sweat' and to get more from the existing building without having to buy or lease more space.

On the face of it this could be seen as a reasonable approach and has many attractions for tenants with an expanding business, or those trying to consolidate their activities into a reduced number of locations. The down side of this approach is that the original building facilities, especially the lifts, are not always able to cope with the additional pressure created by the increased population. The thing to note here is that while the lift systems may have been designed for a population density of 1:14m<sup>2</sup> the other services, toilets, air handling, electrical services, etc were based on a design of 1:10<sup>2</sup>, an anomaly that meant the lift service suffered more than the other building services when increase density levels were imposed.

The idea of increasing building population densities came at a time when the financial markets were buoyant and trading floors were the areas of high population density. Typically this was detailed at 1:7m<sup>2</sup> and trading floors could contain significant numbers of people, so much so that special lift provision was made in many modern buildings to separate the traders lift service from that of the main passenger lifts.

In 2009 a new edition of BCO was published. Section 7 deals with vertical transportation and recognition is given to the changing technology in lift control systems, principally destination

control (DC) as well as the fact that lift system design has moved beyond mathematical calculation to traffic simulation. With the popular uptake of DC systems has come a different means of measuring lift performance, average waiting times (AWT) and time to destination (TTD). From a lift design standpoint the same criteria can now be applied to both conventional and DC systems given simulation techniques provides these details as part of the traffic analysis results.

As well as performance criteria for the up peak BCO 2009 also gives recognition to lunch time traffic performance. This arguably puts more pressure on the lift system than the morning up peak. An average waiting time during the lunch period together with a template for two way and inter floor traffic provides a benchmark for acceptable lift performance.

The publication of BCO 2009 has caused a fundamental shift in the way lift performance is detailed and assessed. In terms of the key point of reference it has moved the emphasis away from handling capacity and interval to average waiting time and time to destination.

In addition to detailing lift performance criteria BCO 2009 also sets out to recognise that density levels have increased and provides guidance on population densities based on 1:12m<sup>2</sup>. Taking account of space utilisation at 80% of the net internal area (NIA) of the building an equivalent density of 1:10 is established. Although not specifically mentioned in Section 7 high density floors are generally recognised as having a density of 1:7m<sup>2</sup> or in some cases 1:6m<sup>2</sup>.

## **HOW BCO 2009 HAS CHANGED THE APPROACH TO DESIGNING AND LETTING BUILDINGS**

From the standpoint of building design and marketing this fundamental shift in lift performance measurement has meant that BCO 2009 is now the main point of reference for letting agents, tenants, developers and consultants. Average waiting times and time to destination are far more tangible to many than interval and handling capacity.

From the developer's perspective the key drivers to letting a building are the three L's; lobbies, loos and lifts. These are the areas which are fitted out as part of the base build shell and core works by the developer. They are the main landlord managed areas and the ones that receive the most attention in terms of design finishes. In many respects the main lobby is a statement of the building's grandeur and is representative of the occupants and who they are. Lifts are a key element in the building as a whole but absolutely essential in terms of being able to provide quick and reliable access to the tenant spaces. Not only is good service required but also the lift interior design is seen as an extension of the lobby finishes, carrying through the expression of the architects design.

For the developer and letting agents, the ability of the lifts to service the building provides a major selling point to potential tenants. It should be recognised that generally letting agents, and some developers, know very little about lifts. However they are acutely aware of what is written in BCO 2009 and it is this that drives one of the main selling points; the lifts are 'BCO 2009 compliant'. So, what does this really mean and is it what the market is looking for?

Developers and letting agents are very aware of the market requirement for higher density levels in both general office and what are now termed 'high density' floors as opposed to perhaps 'trading' floors. Indeed it is the letting and marketing agencies that drive the trend, selling the benefits of higher densities, harder working buildings and a more efficient and cost effective means of managing the business.

Office floors have almost by default moved towards a density of 1:8m<sup>2</sup>, with ‘high density’ floors at 1:7m<sup>2</sup> or even 1:6m<sup>2</sup>. From a lift design perspective this presents a dilemma. What performance criteria do you design to with a much higher level of building population? Clearly, if you base the design on BCO density levels then the building will be under lifted; design to a higher density level then you are not, strictly speaking, BCO compliant.

With the higher density levels now required the key appears to be to design to BCO performance criteria based on the higher levels of density being called for. This inevitably means that more lifts are required to service the building.

With letting agents telling the developers that greater density levels are being sought the developer has to assess the risks associated with either designing to BCO 2009, i.e. 1:12m<sup>2</sup> and 80% utilisation, or, look to a higher level of density, 1:8m<sup>2</sup> perhaps, and find more lifts are required, with the resultant impact of a larger core and perhaps less net lettable area.

Here technology can help to some degree. The move to destination systems provides the main advantage in managing the up peak performance. It is recognised that the ability of DC systems to service lunch time traffic is not as good as conventional systems, but given the 40 second AWT these systems can provide a service to meet the BCO criteria. From a letting and marketing perspective, DC systems are seen as the latest technology and provide a good selling point for the building, albeit it is not always the best solution.

Clearly any building is in competition with other developments and whilst location can be a key issue what the building has to offer as a whole is a major consideration. Important among those factors are lifts and lift performance. A well lifted building with a robust design based on high density levels provides potential tenants with the assurance that the lifts will provide a good service. It will also stand due diligence by the tenants’ consultants and can provide a high degree of future proofing, assuming that not all floors are populated at the higher density levels from day one.

With the more tangible language of lift performance provided by BCO 2009 and a trend to higher density levels letting agents and developers have some key components to add to the sales brochures.

## **HOW LIFT DESIGN INFLUENCES THE SALES APPROACH.**

Most buildings today have some degree of pre letting before building works start. Those developments that are speculative have to try and ensure that the design will attract tenants. The advantage of the speculative buildings is that lead times for tenant occupation are reduced. However, those looking for a ready made solution will have to live within the constraints of the original design and services. To this degree the speculative developer has to try to ensure that what he builds fits with the sectors of the market the development is intended to address, and provides a suitable level of robustness for the future.

The bespoke design allows the developer to tailor the building to a specific tenants needs and provide a building that fits with the requirements of their business. On the other side of the equation is the fact that the tenant may only be occupying part of the building and at some point may decide to move. This leaves the owner with a building that needs to be re-let some considerable time after it was built. To this end the building needs to provide suitable future proofing to allow for a change in use and to have the ability to be refitted for new tenants with their unique needs.

From a lift design perspective what are the elements of base build design that will at least go some way to providing the flexibility needed for the future? Firstly, the lift design has to have the ability

to be adapted to suit varying levels of tenant space take. This obviously means it needs to account for single or multi tenant occupancy both at the original design stage and in the future.

For tall buildings multiple transfer floor options between groups gives a high degree of flexibility. It allows a range of space to be made available, particularly to tenants who are seeking to have a group of lifts dedicated to their own business. This brings obvious compromises in terms of building NIA, location of low rise overrun and machine rooms and lift lobby space. It also means that each group should be capable of serving all floors at the density levels being designed for. While this may seem somewhat excessive, it does offer real flexibility and provides the letting and marketing agents with a key feature when seeking tenants.

Floors	Low	High
12		
11		
10		
9		
8		
7	Transfer	Transfer
6	Transfer	Transfer
5	Transfer	Transfer
4		
3		
2		
1		
0		

Multiple transfer floor options provides flexibility

Another way in which the building design can be enhanced is leaving ‘soft spots’ for the introduction of escalators at a later date, especially to serve the lower floors. Where these floors may be designed for a density of 1:8m<sup>2</sup> initially the introduction of escalators could allow a change to ‘high density’ levels. This has limitations and would only be considered for the first two floors perhaps, but it does provide the building with greater flexibility over its’ life. Escalators do take up space, but for developers and letting agents having the option is seen as a considerable advantage.

Most buildings today in the UK have concrete cores and in some instances of lower rise buildings, 15 to 20 floors, it is necessary to take the whole core to the top of the building for reasons of structural stability. This means the low rise lift shafts extend to the top of the building where the machine room is located. This is another means of providing flexibility within the building lift design whereby the lifts may stop at a predetermined floor but the guides are taken to the top of the shaft. This allows for the low rise lift service to be extended beyond its original level and can provide flexibility in the building going forward. There is a case in point where in one major office building in London this was undertaken and with the aid of destination control the building is now served by a 12 car group.

Floor	Low	High
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		
0		

The low rise shaft extends to the top floor but the lifts can only serve to level 7

The ability of the building design to offer flexible solutions provides the letting and marketing agents with a key differentiating feature. This makes the building more attractive to potential tenants, not only at the time of leasing, but also in the future if the tenant requirements change and they seek to take more space in the same building.

These are examples of buildings where the initial design has been tailored to accommodate the specific requirements of the original tenant, however the ability to be adaptable in future has been recognised during the base build design. This approach provides the developer with office buildings that not only meet the requirements of tenants and potential purchasers but also provide a high degree of flexibility for the foreseeable future. From a commercial, marketing and letting standpoint this gives those buildings a significant advantage over the competition.

The market for letting buildings is highly competitive with prime office development space sought mostly by major corporations and businesses. To secure a major tenant is a significant achievement in the face of stiff competition. To provide the marketing and letting agents with the tools necessary to secure these key tenants, lifts play a major role. Many tenants come from buildings where they have experienced poor lift service with queuing, long waiting times and unreliability. In such circumstances one of the essential criteria of the new building is good lift service. So much so that in some instances service levels have to be maintained with N -1 lifts. This is clearly outside most design criteria but it does illustrate the importance of lift service to organisations that have demanding standards and want to ensure they have robust lift service. The idea that staff may wait for long periods does not fit with the needs of the business where 'time at the desk' is everything.

With a robust and flexible shell and core vertical transportation design the marketing and letting agents are provided with a key ingredient with which to differentiate the development and its importance cannot be emphasised enough. A badly designed lift system with insufficient lifts will never be right. Once the building is built it will always have a reputation for poor lift service and a huge investment is permanently undermined.

## **VERTICAL TRANSPORTATION; MEETING THE TENANT'S REQUIREMENTS**

As well as the lift systems providing a robust and flexible means of aiding the letting of the building there are other key elements of the lift system that the agents and potential tenants look for.

The need to demonstrate that the building is equipped with the latest technology is essential. This extends to the lifts as much as any other part of the building and while 'artificial intelligence' is no longer seen as a major feature, the most obvious technological change has been in the use of destination control systems. Although not new to the lift industry, they have almost become the default system for new buildings, bringing with them the ability to act as an 'up peak booster'. Notwithstanding the shortcomings of the systems in handling two way traffic, especially at lunch times, they are seen as the latest thing in technological terms.

This is a tribute to the marketing ability of the lift industry, who, in the main have been slow to recognise the importance of the system. Nevertheless they have recognised that the system is seen as 'state of the art' and peripheral parts, namely the user interfaces, can be provided with touch screens giving the ability to personalise the 'user experience'.

The ability to offer a personalised service is a major aspiration of companies, as well as letting and marketing agents. The use of landing touch screens and in car displays offers the opportunity to 'tailor' lift travel. The opportunity to display a company logo and business details on screens in the cars and at the lobby's call stations is seen as an extended means of advertising and selling the company message. Some of the recent requests I am aware of include:

- The requirement to group employees of one company in a lift and run a corporate video as the car travels to the floor.
- Have the ability to provide a bespoke 'greeting' message on the landing call station screen, 'Good morning Jack, have a nice day!'
- Run a company promotional video on the car screen for visitors to a particular floor.
- Advise your anticipated travel time while travelling in the lift.

Whilst some of these requests may appear excessive they do demonstrate what the marketing and letting agents are seeking as a means of differentiating one building from the next. These are part of the 'arrival and user experience' and are seen as the means of making you feel better about both the building and your interface to it.

'Green' is an important part of lift design and the need to comply with the BREEAM requirements as part of the design process is a 'must have'. Regenerative drives and power shut down when idle are becoming an increasing part of lift specifications. Although lift power consumption is a small part of the total building usage, percentage savings within the lift element are important and seen by agents and tenants as important.

As an extension of the green agenda, sustainability within the design and life of the lift are now becoming important parts of the approach taken by manufacturers. The need to demonstrate that the lifts form part of the overall strategic approach to building design is assuming ever increasing importance. This is a key factor looked for by letting and marketing agents and the ability to demonstrate that, not only are the lift materials sourced from sustainable materials, but also the ability to recycle equipment at the end of its life are taking on an ever increasing importance.

As with all buildings there is now great emphasis on security. In this the lifts have an important part to play. There is now a link between major lift suppliers and security companies as part of an effort to provide a 'total' lift/security solution. The move is part of the growing need to reassure people



they are safe, not only at work, but also in their own properties. In the workplace the ability to demonstrate that security is high on the employers' agenda is a significant driver and there is great emphasis on security systems.

Card readers are now the main means of access to most buildings. Their use on the call station of destination systems is an option widely available. This not only provides a means of ensuring the building user only has access to their designated floors, but also provides a level of assurance to other tenants that their own floors are more secure; albeit the main point of security to the tenant demise is generally at the tenants lift lobby where further card readers are deployed. This type of facility is also seen as 'state of the art' and requires a high level of interface between the lift and security systems. This can be challenging but it is seen as technologically advanced and adds to the feeling that tenants are secure; a key selling point.

Increasingly the ability to interface to a smart phone or a tablet is seen as both essential and modern. Lift systems are now being designed with facilities that will allow remote calling of a lift. This is in its infancy but will increasingly become a standard feature. While this may sound a good idea to the marketing agent in reality there are many variables to cater for, your location relative to the lift, your walking speed, distractions and interruptions on your way to the lift lobby. I'm sure there are many others and this will perhaps fall into the category of 'it sounded a good idea at the time'.

However, there are other areas where information to a smart phone or tablet could provide useful information to designated users, such as facilities managers, lift companies and monitoring consultants. Details of lift service levels, breakdowns and performance data could be sent to hand held devices and provide a means of identifying problems at an early stage. Currently this type of information is used in remote monitoring, generally by the lift company, but its wider availability to designated users can only be a matter of time. When it does arrive it will be another useful selling aid to the agents.

The linking of the lift system to turnstiles is something that has been seen as 'state of the art' by agents. However building users, consultants and the industry are beginning to move away from the idea, especially where longer walking distances are involved. Better to have the turnstile provide the 'right of passage' and the passenger register their destination call at or near the lift lobby. The only possible exception is where the turnstiles are directly in front of the lift lobby as walking distances are short

As with all office buildings each is unique in some way and the needs and requirements of tenants and building users are different in each case. However the ability for lifts and lift systems to be able to be adapted to suit the needs of particular tenants is fundamental to the marketing and letting of the building. The tenant is 'King' and whatever needs to be done to satisfy his requirements, either totally or in part, is an essential part of the selling strategy.

## **A LIFT RATING FOR BUILDINGS?**

One of the items that has become something of an industry talking point is a rating system for lift service in buildings. Currently CIBSE Guide D [3] details a star rating system which on the face of it sound reasonable. The idea that criteria can be established to provide a system of star rating does have logic and would allow an instant assessment of a buildings lifting capability.

There are however some significant drawbacks to the star rating approach. In the first instance who establishes the rating? Is it the lift supplier, the consultant, the building owner or some other body? Whoever it may be there are always going to be grey areas and borderline cases. We are all too

aware that traffic figures can be 'adjusted' through changes to the inputs and this could lead to unrealistic performance criteria being used just to achieve the right level of star rating.

It would be natural for the developer or owner to want the highest star rating for their latest building and this would undoubtedly be a very useful piece of marketing information to tempt potential tenants. The difficulty here is that the rating system sets too rigid a line with no flexibility within the measurement criteria. Is it realistic to classify a system with 20 seconds AWT as 5 star while a system with 21 seconds AWT is 4 stars? The fact that the star rating system does not align with the current BCO criteria is recognised by consultants and those close to the industry but given the BCO document is the main point of reference for developers and agents the differences are not highlighted.

Whilst CIBSE Guide D states the star rating criteria only applies to new modern office buildings it would not be unreasonable for owners to seek to apply it to existing and modernised buildings, especially if they thought it would give them an edge in the market. We know that many, until the early/mid 2000's buildings, were still being designed on criteria of 30 second interval with a 12.5 % to 15% handling capacity and a density of 1:14m<sup>2</sup> with absenteeism. Even allowing for the use of destination control the lifts in these buildings will never meet the current BCO performance criteria let alone that of a building with a density of 1:8m<sup>2</sup>. So where would that leave those buildings in the eyes of the marketing and letting agents? I would suggest there would be a lot of very disgruntled owners and tenants who 'always knew the lifts were no good!'

The star rating system may seem like a good idea but in reality it cannot be used as an effective means of ranking lift performance. From the standpoint of the 'market' it would be used as a black and white measure and lead to owners, agents and tenants arguing over service charges and rents base on the star rating of the lifts.

In terms of what the market is looking for, 'BCO Complaint' is the key phrase. Whether that is based on a density of 1:10m<sup>2</sup> or 1:8m<sup>2</sup>, as long as the densities used are understood by all concerned there is little risk of misunderstanding or ambiguity.

## **CONCLUSIONS**

BCO 2009 has fundamentally changed the way lift performance is calculated and measured. It has recognised the use of simulation as a tool in the designing of lift systems and provides an easier means of assessing performance through the change in measurement criteria. It has also become the key point of reference for developers, consultants and letting agents.

Higher density levels and future flexibility are driving the need to provide robust designs that can be adapted to prolong the life of buildings and offer real long term investments for developers. Many of today's building do have the ability to adapt; something not always shared by their counterparts of the 1960's, 70's and 80's.

In today's competitive market place the development and letting of buildings is a complex process and like any product it has to meet the needs of the market. The expectations of the end user, the ability to deliver and flexibility for future adaptation are major parts of today's market requirements. New developments represent huge investments and getting things wrong at the design stage will leave a lasting legacy that will be stamped large on the building. Once a building gets a reputation for poor lift service it is almost impossible to erase, especially if the building is under lifted as opposed to having lift systems that are poorly adjusted or set up.

The market place is driven by letting and marketing agents who have little understanding of lifts but they know only too well that 'BCO Compliant' sells the message that the building is well served. The knowledge that the vertical transportation is designed as an integral part of a flexible approach provides both developers and the agents with an edge in the market place and provides tenants with the comfort that the building could cater for their future needs. It will stand the test of due diligence and deliver tenant satisfaction. This combined with the latest technical innovation, state of the art systems and equipment is a key criteria in selling to sophisticated tenants and demanding businesses.

The arrival and user 'experience' are all part of both the selling process and the ability to tailor interfaces, graphics and visitor management to the corporate image. A personalised journey in a 'safe' environment helps to send the message that the building reflects what the business is and 'who we are' and provides a place where employees are happy to work. These are seen as essential parts of providing an environment where people can focus on work and not be distracted by poor lift performance with long waiting times and the inability of systems to adapt to the changing world.

The question remains as to exactly what the true density levels in modern buildings really are but there is no ignoring the fact that buildings are having to work harder and 'earn their keep'.

The changing dynamic in terms of technology means that the ability of modern buildings to adapt is essential. This provides long term confidence to the developers and owners and makes the huge investment sustainable. The only real question is:

Has the tester set everything up correctly?

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## The revision of EN81-1 and EN81-2 to become EN81-20 and EN81-50

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**Abstract.** 1998 saw the last full edition of EN81-1/2 published in order to satisfy the requirements of the Lifts Directive. Since that date more than 400 experts in lift technology have been rewriting those two base standards and in 2014 that work will finally come to fruition with the publication of EN 81-20/50. This paper addresses the reasons for some of the changes, elaborates on the major differences to the new EN 81-20/50 standards from their EN 81-1/2 counterparts and outlines the implementation of these documents which are set to become the first global prescriptive standards for lifts.

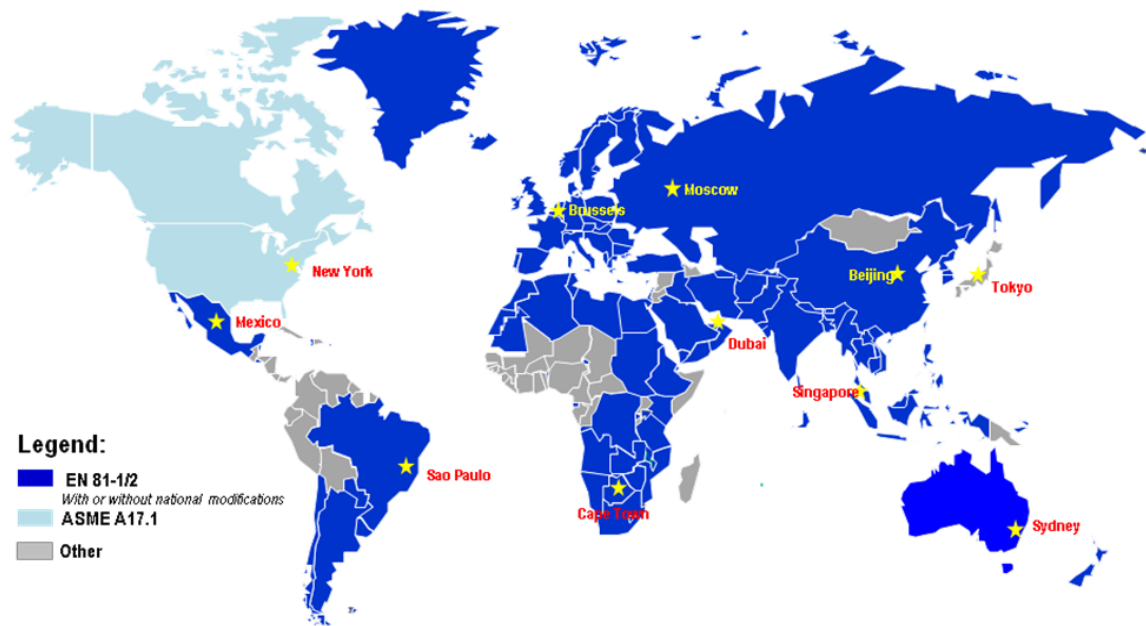
### INTRODUCTION

When EN81-1 and EN81-2 were last subjected to a light revision it was due to the introduction of the Lifts Directive in 1998. At that time it was felt by all those involved that something much more in-depth would soon be needed since the standard was beginning to show signs of its age, due to being first published in the mid 1980's. Also at that time it was identified that two major amendments were needed to bring these standards up to what is commonly referred to as "state of the art" in the areas of programmable safety systems (PESSRAL) and machine room-less lifts (MRL's).

Since CEN rules only allow any standard to undergo such revisions three times before it has to be re-published under a new year reference it was decided to start work on the next versions of these standards in parallel to these amendments.

When the Machinery Directive was then revised, forcing the third and final amendment to EN81-1 and EN81-2 to remove lifts operating at speeds below 0,15 m/s and to include stopping and leveling accuracy, it was also decided to include provisions for the protection against uncontrolled movement with open doors.

This effectively sealed the fate of the two most widely used standards for lifts in the world (see Fig 1) and work was intensified on their replacements.



**Figure 1** – Usage of EN81-1 and EN81-2 at global level

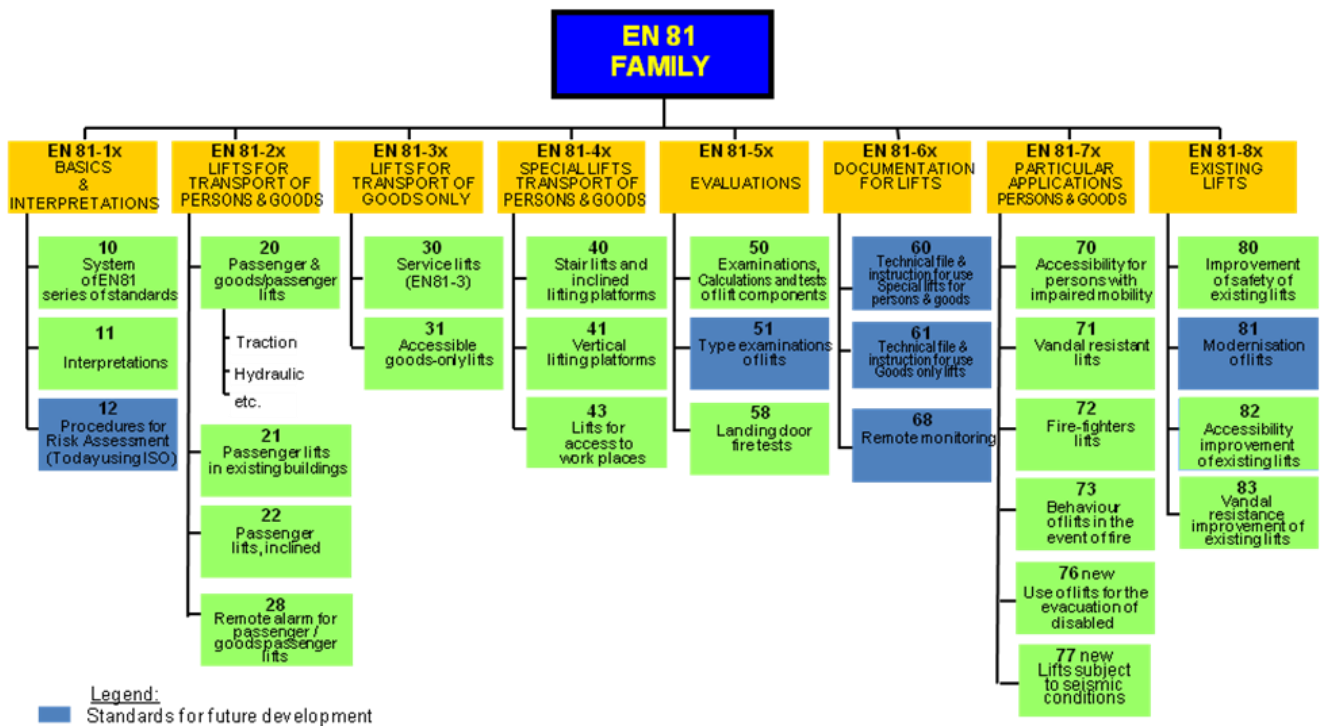
## PLANNING AND INPUT

So how do you go about re-writing standards which are used not only within Europe but more widely around the world?

The answer is “very carefully!” and with a lot of planning.

The first task was to identify how the standards might look in the future and how to make them easier to work on. The result was the publication of TR81-10 which planned out the future of the whole EN81 series. (See Fig 2)

Therefore it was decided to combine EN81-1 and EN81-2 into a single new standard, EN81-20 and for sections involving validation of design by calculations, Type Testing, etc. to go into a new EN81-50.



**Figure 2 – The new EN81 Series**

After this was decided then the task of reviewing the inputs into any new standard began, which included for the first time any partner organization to CEN including those in the Far East who install more than 400,000 lifts to EN81 series codes every year. The full list of inputs can be seen in Figure 3.

Once these inputs were fully understood packages of work were assigned to 18 specialist teams to develop into firm proposals for inclusion into these new standards. In this way every single clause of the existing standard was considered and either confirmed or altered accordingly. A total of more than 400 experts in lift technology have therefore been involved in the creation of these new standards.



**Figure 3 – Inputs to the revision**

## MAJOR CHANGES

One of the most difficult things to change, but one which people have the most affinity with, is that of the numbering system. Anyone working with EN81-1/2 for any length of time will start to learn specific clause references and so the documents become embedded in memory.

Due to the requirements of new CEN rules all new standards must be drafted in a common way, which results in all technical clauses being encompassed within Clause 5. Therefore every clause in the existing standards now has a new number which might extend to six digits. e.g. **5.1.2.3.4.5**


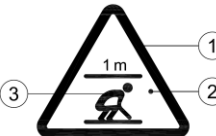

Whilst it is impossible to give all of the changes made to these documents in such a short presentation, some of the major changes and their rationale are described below.

**The Well.** A review of the requirements for this area has led to several changes having far reaching implications on installation design.

- a) The ventilation of the well is now considered as an architectural issue rather than a concern of the lift designer. This is due to many changes throughout Europe's building regulations with the result that statements about well ventilation become meaningless in certain countries. The manufacturer will have to give details of the heat output of the lift installation to the building designer.
- b) The strength of materials used to construct the well has been altered to give limits to permanent and elastic deformation under defined forces. At the same time lift wells made of glass must be of laminate material throughout their full height to protect from breakage of panels.
- c) Where lift cars are not required to have balustrades on the car roof to protect from falling there must be no ledges greater than 150 mm in order to prevent maintenance engineers and inspection persons stepping off the car.
- d) The option to use a solid pier under a counterweight to protect accessible spaces below the well is now deleted.
- e) Pits deeper than 2.5 m must have an access door at the base of the pit. Access ladders to pits less than 2.5 m are now fully defined in EN81-20.
- f) Counterweight screens are redefined in strength and to prevent access from behind, whilst still allowing inspection to take place. They must have a label indicating the design clearances under the buffer to ensure correct adjustment and re-roping.
- g) Pits are to be fitted with inspection control stations to allow engineers in the pit to have full control of the lift in order to maintain equipment mounted under the car, such as safety gear, guide shoes, etc.
- h) Refuge spaces above and below the car are redefined (see **Table 1**);
  - There must be one refuge space for each person working in that area.
  - Refuge spaces are defined as standing, crouching and laying positions with signs stating which is provided.
  - All refuge spaces in the same area must be of the same type

– All refuge spaces are increase in size from EN81-1/2

i) Lighting requirements remain at EN81-1/2 levels with the exception of ambient lighting in scenic well no longer to be allowed to contribute to the well lighting. There is an addition of an emergency light on the car roof.

Type	Posture	Pictogram	Horizontal dimensions of the refuge space (m x m)	Height of the refuge space (m)
1	Standing		0,40 x 0,50	2,00
2	Crouching		0,50 x 0,70	1,00
3	Laying		0,70 x 1,00	0,50
①: Black colour ②: Yellow colour ③: Black colour				

**Table 1** – Refuge space dimensions and pictograms

**Machinery Spaces.** Whilst this area underwent a complete revision in 2006 with the introduction of MRL technology some changes have been made to reflect the state of the art. This includes improved provision for access to these spaces and light levels in pulley rooms and at emergency and test panels.

Clear heights of entrances to these areas and the working space within have been altered to 2.0 m and 2.1 m respectively.

Where working areas in the well are from the car roof and blocking devices are employed to prevent car movement, then there must be a permanent means of escape to prevent engineers from becoming trapped in these areas.

Sprinklers are now allowed in the well, but before they discharge the lift must be sent to the main exit level and the lift parked with the doors open.

Access to working areas is now allowed via private premises on agreement with the building owner concerning provision of access for maintenance and rescue. This however may be subject to National Regulation which requires access always via public areas.



**Entrances (Car and Landing).** One of the largest changes has been that made to the car and landing doors. These have now been increased in strength and door retainers added to improve integrity under impact conditions. To this effect all doors, not only those made of glass must be subject to pendulum testing with increased impacts from those in EN81-1/2.

After such testing the doors must be within certain defined limits regarding permanent deformation.

Glass doors are now to be provided with increased protection for the “drawing in” of children’s hands. This includes reduced clearances over the lifetime of the doors and limitation of opening force from the door operator.

All power doors must be fitted with non-contact protection devices, which when not able to detect persons must either reduce the door impact force or take the lift out of service.

New limitations have been placed on the height of the unlocking mechanism to avoid persons falling into the well whilst trying to unlock and open doors at the same time.

All car doors are now to be fitted with a “restrictor” which prevents opening from inside the car by more than 50 mm when outside the unlocking zone.

**Lift Car.** The measurement of the floor area at the lift car entrances has been re-defined in terms of overall car floor area. This to bring consistency with ISO 4190 car dimensions.

In addition the materials used inside the car are now subject to fire rating classifications and decorative mirrors are to be made from safety glass. Cars are to have increased normal use lux lighting levels and a defined emergency lighting level.

The requirements concerning loading devices which enter the car to load and unload the lifts, but do not travel with it have been clarified in order to ensure safety under overload conditions.

Outside the car there are new requirements for the strength of the car apron and car roof balustrade, whilst all car roofs must not be provide with a toe board to help protect against objects falling from the car roof.

**Suspension Systems.** Whilst there have been some minor changes the inclusion of suspension systems other than conventional wire rope is to take place at the first revision of EN81-20.

**Safety Gear, governors, buffers and UCM.** A decision was taken by the working groups not to make sweeping changes to the requirements of type tested components since these were seen throughout the world as being sufficiently effective. However two items have been include in order to clarify existing requirements.

- a) The speed governor must activate the safety gear within 250mm of downwards movement of the car or counterweight. This is in order to ensure that the speed of the lift is not beyond the capacity of the safety gear if the governor misses its first engagement point.
- b) A limit of 6g has been placed upon the peak deceleration of buffers at time intervals less than 0.04 s to restrict manufacturers to reasonable levels. This since the effect of high deceleration at short time intervals has never been studied.

Type testing of UCM means at component level, rather than complete systems, is now allowed and the provision for lifts without means of re-levelling clarified.

**Lift Machine.** Little has changed here for conventional lifts (non MRL) with the exception that it must now be possible to check each brake set, from outside the well, for failure in order to ensure the lift is able to be slowed and stopped with one set inoperative.

The requirements for emergency operations have been reviews with the following results;

- The brake must be able to be released manually from outside the well even under failure of the main power supply.
- With brake open and car loaded to +/- 10% of balanced rated load the car must move under gravity or by manual means or electromechanical means with backup supply, available at site.
- If the manual effort to move the car with +/- 10% of balanced rated load greater than 150N then electromechanical means with backup supply, available at site to be provided.

**Electric installations and appliances.** One of the main areas of the standards to be completely overhauled is that of the electrical installation, which has not changed in any substantive way since the mid 1980's. Whilst PESSRAL systems were added in 2006, the rest of the electrical systems remained unaltered.

This has changed dramatically with the introduction of EN81-20 which now requires the installation to be in conformity with EN 60204-1. This means some areas of the existing standards have been removed from EN81-20 since it is not allowed to repeat the content of another EN standard.

Other areas have been added, such as requirements for RCD protection, protection from heat emitting components and the requirements of other EN standards for basic electrical protection and the design and use of contactors, etc.

**Controls.** The following requirements have been added/amended;

- New requirements for control buttons for the inspection stations (run button, button marking and colour, etc.)
- New requirements for protection of maintenance operations
- New requirements to reduce speed under inspection control when less than 2m clearance.
- New requirements for landing and car door by-pass

**Other Modifications, Additions and Deletions.**

- Annex E (NEW) Building Interfaces  
New informative annex for building interfaces including support of loads on structure, guide rails and ventilation
- Annex F (NEW) Pit Ladder  
New requirements for pit access ladders
- Annex G Proof of guide rails  
Calculations modified/corrected, some examples deleted

- Annex K to EN81-1 Top clearances for traction drive lifts (Traction)  
Deleted
- Annex K to EN81-2 Calculations of rams, cylinders, rigid pipes and fittings (Hydraulic)  
Calculations modified/corrected
- Annex L to EN81-1 Necessary buffer stroke (Traction)  
Deleted
- Annex M to EN81-1 Traction evaluation (Traction)  
Calculations modified/corrected
- Annex N to EN81-1 Evaluation of safety factor for suspension ropes (Traction)  
Calculations modified/corrected

## **PUBLIC ENQUIRY**

One of the most impressive statistics of the creation of EN81-20 and EN81-50 is that found within the Public Enquiry stage. During this period all National Standards Bodies in Europe and those partner organizations (of which there are 18 countries represented) were encouraged to make comments on these new proposals.

What was something of a surprise to the drafting committee was the seriousness with which this process was carried out by those organisations, reflecting the importance they place on these documents.

After all comments had been received, sorted and verified a total of 4200 comments had been made, the majority of which were against EN81-20.

The resolution of these comments has taken more than a year to complete, with the result of a much better standard, more easily understood and, hopefully, acceptable to all involved.

These final documents were submitted to the CEN Formal Vote process in July 2013.

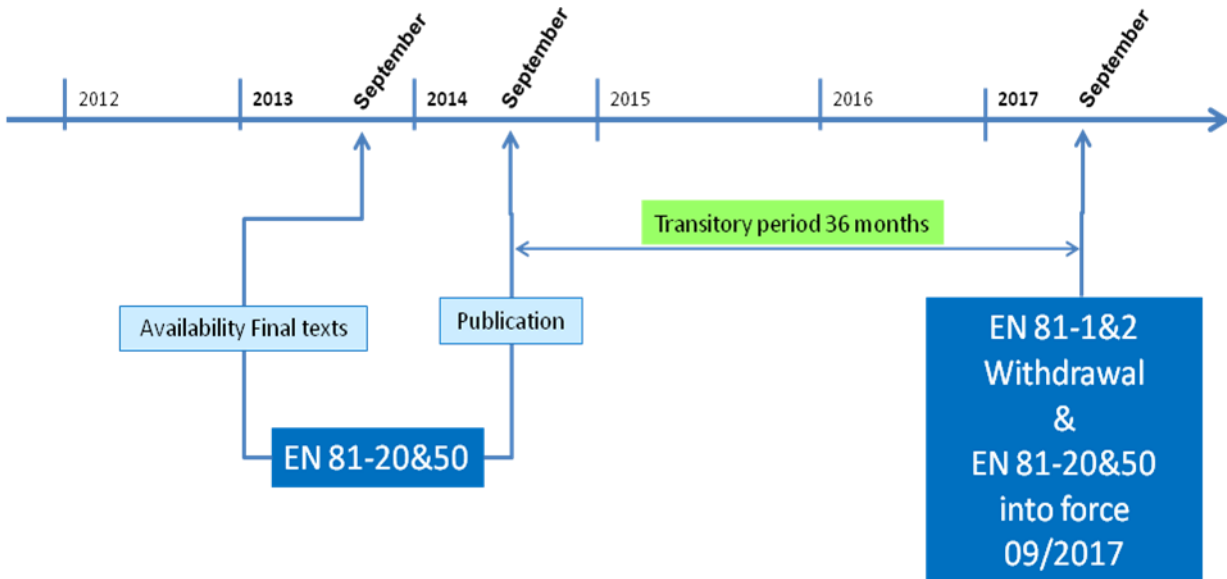
## **FORMAL VOTE AND IMPLEMENTATION**

The next stages are for the main TC10 committee to accept the documents and then transmit it to CEN. Once received they will dispatch them to various consultants, such as those for machinery, noise, etc for review before translation into the French and German versions.

Once available these are then transmitted to the National Standards Bodies in Europe for formal acceptance. Whilst those outside of Europe have no vote during this process countries such as China have already stated their intention to adopt them as their National Standards when finally published.

This Final publication is scheduled to be no later than September 2014.

Once published there will be a period of duality between the new and old standards, with both being acceptable as a means of satisfying the Lifts Directive until September 2017, when EN81-1 and EN81-2 will be formally withdrawn. (See **Fig 4**)



**Figure 4 – Project Timescale**

The final retirement of these stalwart standards of our industry will be a bitter-sweet day for CEN/TC10/WG1, the committee responsible for their creation, amendment, interpretation and finally their replacement.

We can only hope that these new standards are held with equal high regard as those existing, by all the countries that today rely on EN81-1 and EN81-2 for provision of a globally acceptable level of safety.

# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Vibration Problems in Lift and Escalator Systems: Analysis Techniques and Mitigation Strategies

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**Abstract.** The operation of lift and escalator installations is often affected by vibrations and vibro-acoustic noise. This leads to poor ride quality and a high level of dynamic stresses which may result in damage to the installation. Thus, a good understanding of vibration phenomena occurring in lifts and escalator systems is essential. Lift and escalator systems employ components rotating and translating at speed. Those include elastic tension members such as long ropes, cables, chains and belts. Due to their flexibility and loading conditions they are susceptible to vibration and their dynamic characteristics such as stiffness, mass and damping are time-varying. Thus, the analyst and the designer should be aware that the natural frequencies of a lift and escalator installation change with the time and speed of the transport motion. In lift systems the sources of excitation include the inertial load due to the system acceleration/deceleration profile; periodic excitation caused by the host building structure sway; excitation at the sheave from the drive machine; excitation at the car due to the car-guide rail interaction and aerodynamic effects. Vibration (and noise) in chain-driven escalator installations are often caused by the discrete nature of the chain links and their interactions with the sprocket. The dynamic loads produced by impact between the engaging roller and sprocket surface combined with polygonal action lead to excessive transverse vibrations of the chain. This in turn results in excessive friction wear which reduces the safe service life of the installation. The issues relevant to the vibration theory, modelling, testing and analysis of the dynamic response of lift and escalator systems are addressed in the paper. Then, passive, semi-active and active strategies to minimize the effects of adverse dynamic response of the system are discussed, so that the installation can operate under these conditions without alarm.

### INTRODUCTION

The operation of lift and escalator installations is often affected by vibrations and associated vibro-acoustic noise. This leads to poor *ride quality* and a high level of dynamic stresses which may result in damage to the installation [1,2]. Thus, a good understanding of vibration phenomena occurring in lifts and escalator systems is essential in order to design a system which will satisfy ever demanding ride quality criteria. In this extended abstract the main issues concerning vibration problems arising in lift and escalator systems (vibrations in moving walks systems are also mentioned) are briefly discussed. Then, possible strategies to minimize the effects of adverse dynamic response of such systems are reviewed.

### LIFT SYSTEMS

The underlying causes of vibration in an elevator system are varied, including poorly aligned guide rail joints, eccentric pulleys and sheaves, systematic resonance in the electronic control system, and gear and motor generated vibrations [1].

**Vertical Car/ Counterweight Vibrations.** In the vertical direction, the elevator car and counterweight are free to move and can oscillate on the ‘spring’ of the suspension ropes as shown in Fig. 1(a). The diagram presented in Fig. 1(b) illustrates a simplified vibration model of a lift car/ counterweight assembly. In this model  $x(t)$  is a vertical displacement of the car/ counterweight

represented by an effective (equivalent) mass  $m_e$  suspended on a spring of an effective constant  $k_e$ . Damping in the system is represented by a *viscous damping* element of an effective damping constant  $c_e$ . Noting that there are  $n$  ropes,  $E$  is the modulus of elasticity and  $A$  denotes the effective cross-sectional area of each rope, with the roping configuration assumed as 1:1 we define the effective stiffness of the suspension system at the car side as

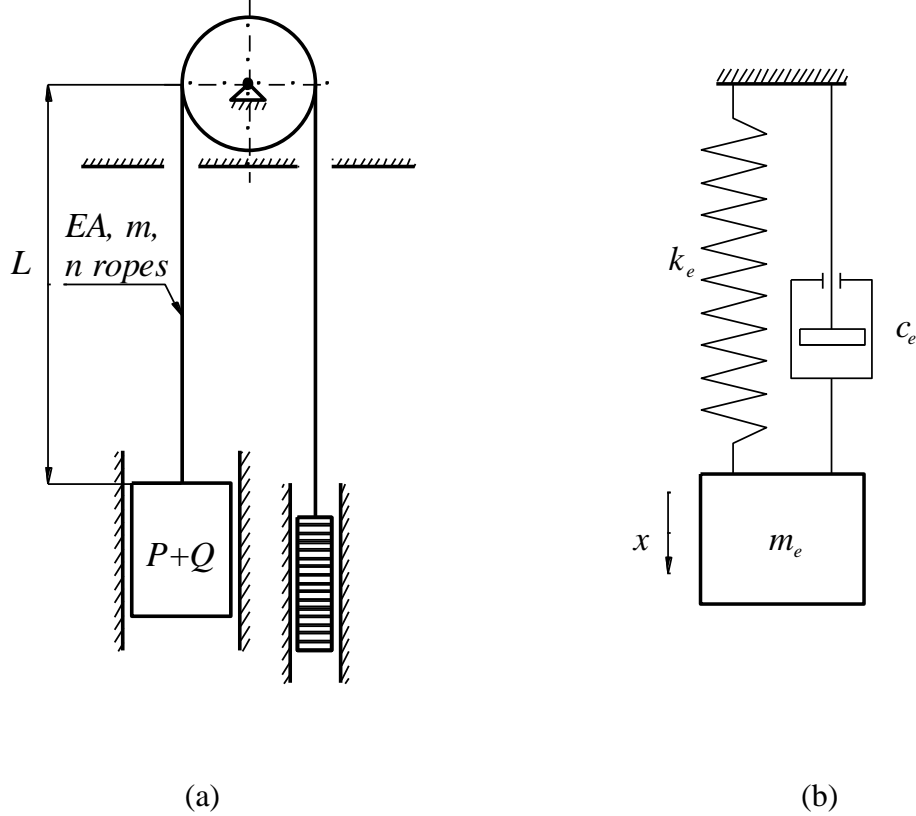


Figure 1.

$$k_e = n \frac{EA}{L} \quad (1)$$

where  $L$  is the length of the ropes at the car side. The equivalent mass of the car and suspension ropes at the car side when the lift is stationary is given by the following expression [3]

$$m_e = P + \alpha Q + \frac{1}{3} nmL \quad (2)$$

where  $P$  is the mass of an empty car,  $Q$  represents rated load and  $\alpha$  is a 'loading factor' (when  $\alpha = 1$  the car is carrying rated load). The quantity defined as

$$\omega_n = \sqrt{\frac{k_e}{m_e}} \quad (3)$$

is the natural frequency of the system. An important feature of the lift system is that the suspension ropes are of time varying length during the lift motion ( $L = L(t)$ ). Furthermore, the number of passengers on board changes ( $0 \leq \alpha \leq 1$ ). Consequently, the dynamic characteristics vary during travel, rendering the system non-stationary [4].

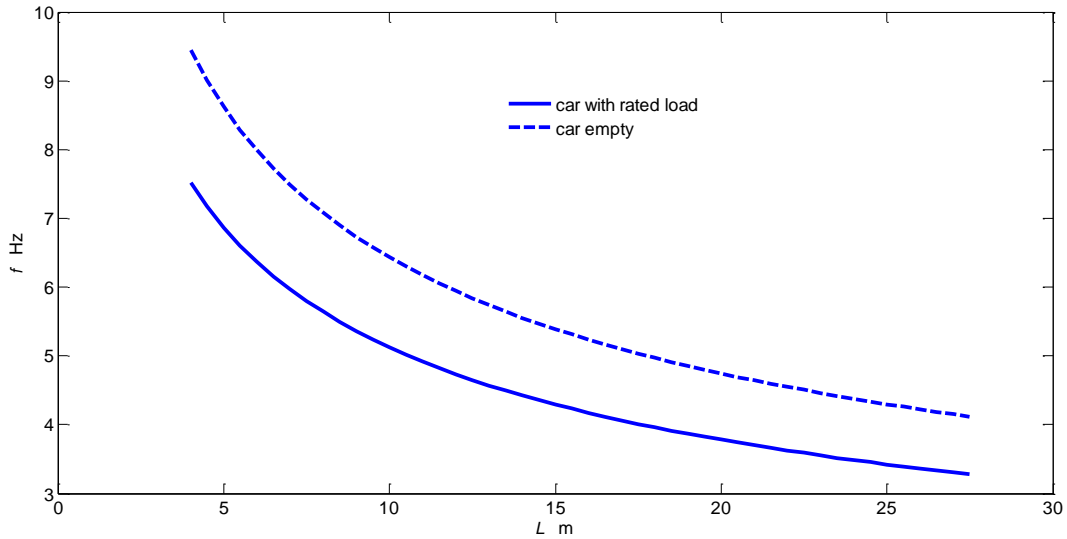


Figure 2. The variation of the natural frequencies with position of the car (determined in terms of  $L$ ).

Fig. 2 shows the variation of the natural frequencies of a car of mass  $P = 15800$  kg (for loaded and empty conditions; with  $Q = 9100$  kg) with the position of the car in a hoistway for a lift installation of travel height  $H = 23.6$  m. The car is suspended on  $n = 10$  Drako 300T ropes of  $d = 16$  mm and mass per meter  $m = 1.1$  kg/m each. It is evident that the frequencies are increasing when the car is moved from its position at the bottom landing upwards and the length of the ropes  $L$  is getting shorter. The frequencies of the system with the car carrying no load are higher than the frequencies with the car with rated load. An adverse situation arises when one of the slowly varying rope frequencies approaches near the frequency of a periodic excitation existing in the system. This results in a *passage through resonance* [4]. In such case the lift car will not vibrate throughout its travel, but will pass through a resonant vibration at some particular stage in the travel. Very often, this vibration stage occurs at or near the highest floor, as the suspension ropes become short. Fig. 3 illustrates transient vibrations which might be experienced.

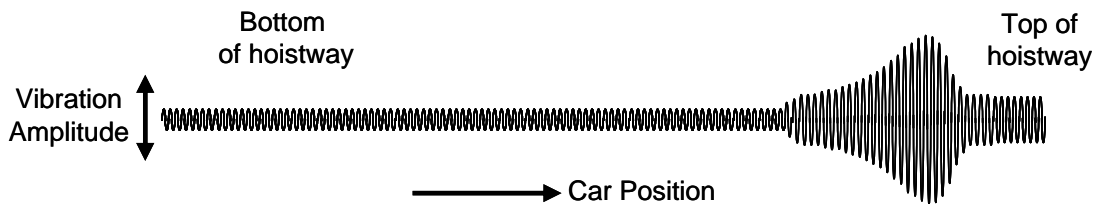


Figure 3. Transient vibration of a lift car.

**Horizontal Car/ Counterweight Vibrations.** In the horizontal direction a lift car is constrained by the guiding system. The guide rail irregularities introduce lateral excitation to the car during its travel. A simple model of a car of mass  $M$  moving at a constant speed  $V$  and guided by rails  $R_1$  and  $R_2$  is shown in Fig. 4(a). The guide shoes are represented by spring – viscous damper elements of coefficient of stiffness  $k$  and viscous damping coefficient  $c$ , respectively (in this model the influence of the hoist rope stiffness, damping and inertial characteristics is not accounted for).

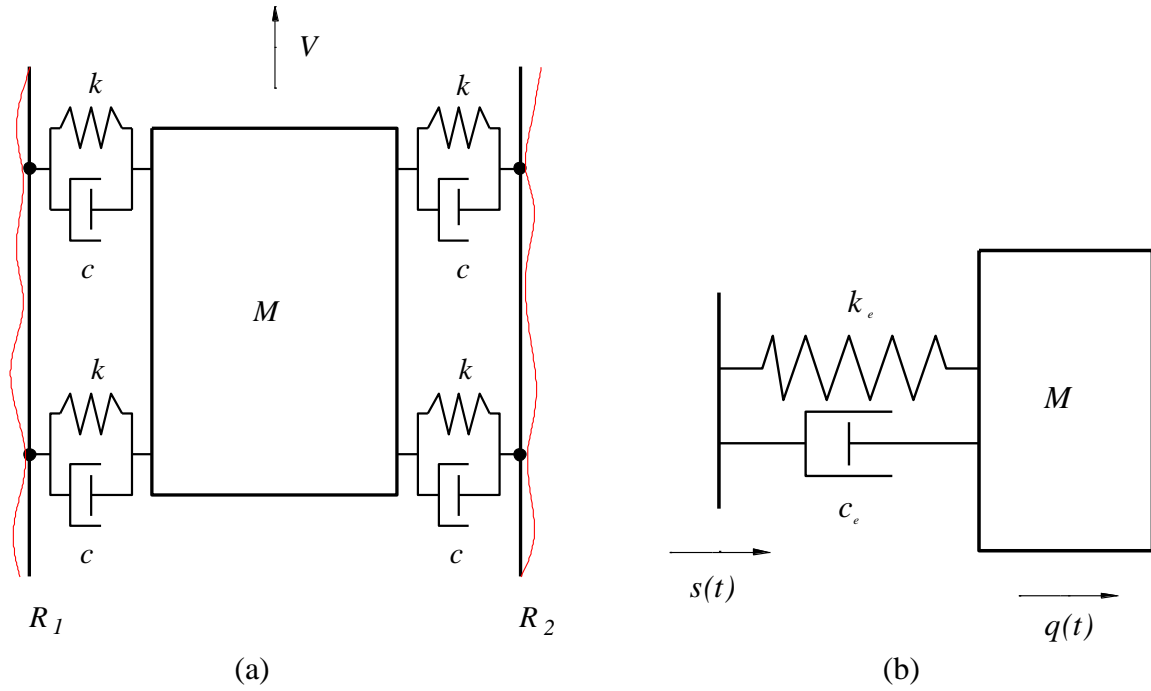


Figure 4. Simple model of a lift car guided by rails.

In vibration analysis this model can be simplified further and an equivalent single-degree-of-freedom (SDOF) system as shown in Fig. 4(b), where the lateral (horizontal) displacement of the car is denoted as  $q(t)$ . In this representation the combined stiffness and damping of the car – guide rail interface is given by the equivalent stiffness coefficient  $k_e$  and the equivalent damping coefficient  $c_e$ . The unevenness and/or bending of the guide rails results in a kinematic excitation represented by base motion  $s(t)$ . The excitation imparted by the rail joints can be approximated by a harmonic function  $s(t) = s_m \cos \Omega t$  of the fundamental frequency  $\Omega = \frac{2\pi}{\lambda} V$ , where  $\lambda$  represents a

wavelength equal to the distance between the joints. Subsequently, if  $r = \frac{\Omega}{\omega}$ , where  $\omega = \sqrt{\frac{k_e}{M}}$  is the natural frequency of the system, the ratio of the maximum steady-state response amplitude  $q_m$  to the maximum input displacement  $s_m$  is given by

$$\frac{q_m}{s_m} = \sqrt{\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}} \quad (4)$$

where  $\zeta = \frac{c_e}{2M\omega}$  denotes the damping factor. The quantity defined by Eq. 4 is referred to as *displacement transmissibility*. This ratio is plotted in Fig. 5 for various values of  $\zeta$ . It is evident from this plot that if  $r$  is greater than  $\sqrt{2} \approx 1.41$ , the vibration amplitude of the car is smaller than the amplitude of rail displacement and isolation occurs. Near the resonance ( $r = 1$ ) the transmissibility is determined by the amount of damping, namely by the value of  $\zeta$  and the larger the damping ratio, the better the resonance suppression. However, in the isolation region the smaller the value of  $\zeta$ , the better the isolation. For a damping ratio of 50% ( $\zeta = 0.5$ ) the amplification at resonant frequency is in the range 1.5 to 2. Simultaneously, the car – rail guide interface provides satisfactory isolation for the frequency range of  $r > \sqrt{2}$ . The analysis of the SDOF model of the car – rail interactions provides some fundamental understanding of the dynamic behaviour of the lift car. However, the suspension system should be included into the model in order to investigate the influence of the guide rail excitation on the overall performance of the lift system [4].



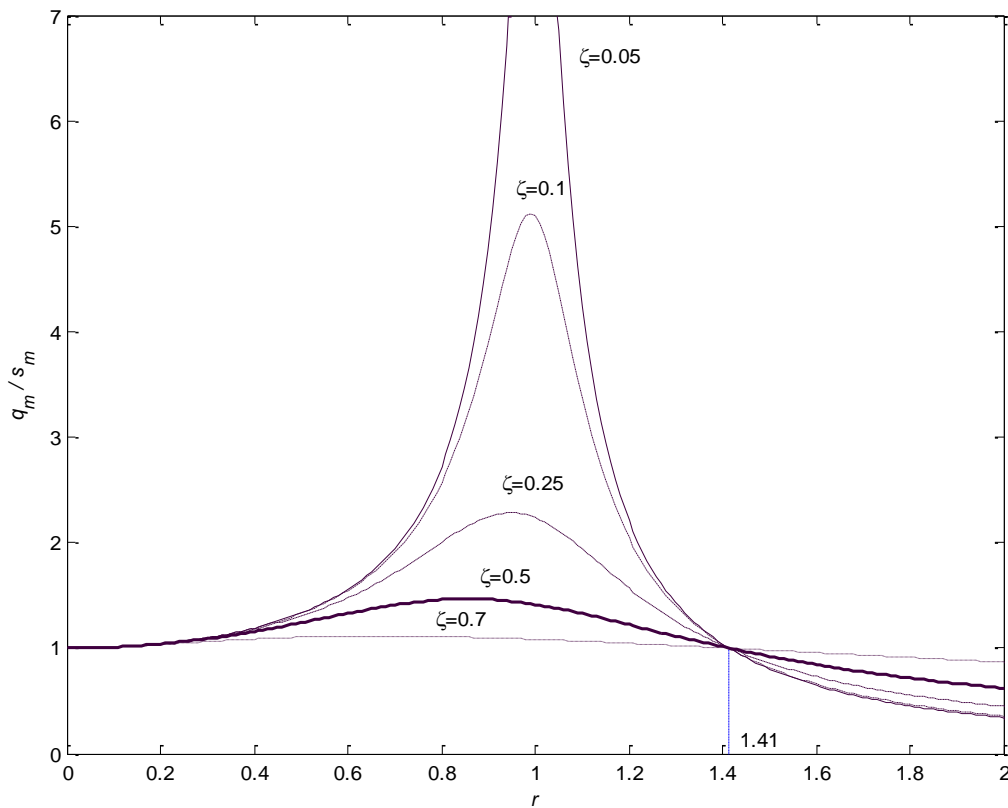


Figure 5. Displacement transmissibility.

## ESCALATOR AND MOVING WALK SYSTEMS

Escalators and moving walks are generally similar in basic construction. They are chain-driven; with the chain being a major source of vibration. Vibrations are also induced by steps, rotating imbalance, misalignment, motor drive system dynamics and other typical causes.

**Chain Dynamics.** Chain dynamic behaviour is affected by the discrete nature of the chain links and sprocket teeth. Compared to traction driven elevators with the car and counterweight suspended on steel wire ropes (or on other means such as synthetic fibre ropes or coated steel belts) this discrete nature makes the chain drive unique with both advantages as disadvantages. The advantage is that the drive is a positive drive and no slip between the chain and the wheel (sprocket). However, the dynamic behaviour of chain drives is complex and they suffer from high level of noise and vibration [6]. Transverse and longitudinal vibrations of the chain are caused by the combined effect of so called polygonal action and impacts between the rollers and sprockets [7].

**Impact Loads.** The impact between the engaging roller and the sprocket is due to the velocity of the roller relative to the sprocket surface as the roller seats.

**Polygonal Action.** The polygonal action (effect) takes place due to the fact that the chain lying on the sprocket forms a polygon rather than a circle (see Fig. 6). This leads to motion of the chain with fluctuating speed, with the maximum and minimum speed determined as

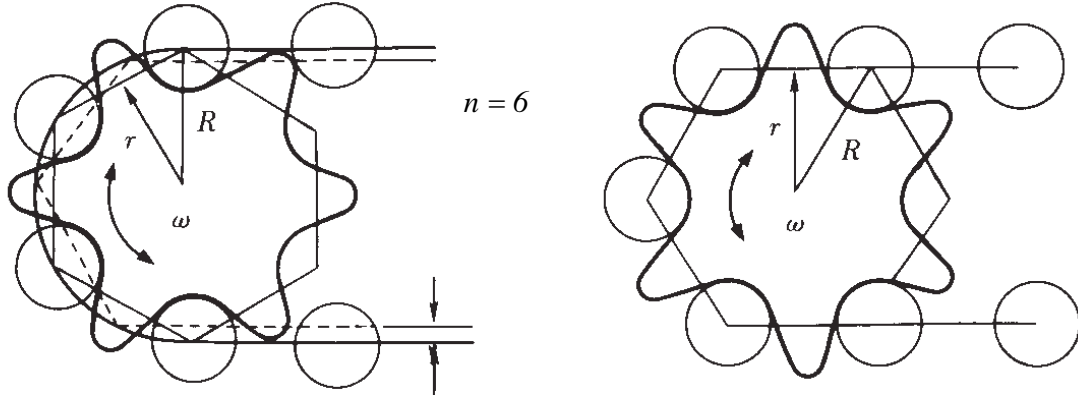


Figure 6. Polygonal effect.

$$\begin{aligned} v_{max} &= \omega R \\ v_{min} &= \omega r \end{aligned} \quad (5)$$

where  $\omega$  is the rotational speed of the sprocket (in rad/s) and the relationship between the radius minimum  $r$  and the maximum radius  $R$  is given as

$$r = R \cos\left(\frac{\pi}{n}\right) \quad (6)$$

where  $n$  represents the number of teeth in the sprocket. The ratio of speed change (fluctuation) can be quantified by the following equation

$$\eta = \frac{v_{max} - v_{min}}{v_{max}} = 1 - \cos\left(\frac{\pi}{n}\right) \quad (7)$$

It is evident that the transport speed fluctuation is reduced if the number of teeth is increased (see Fig. 7). The chain vibrates according to the speed fluctuation and vibrations will be reduced if the number of teeth is increased. The polygonal effects lead to external and parametric excitations. The equation of transverse vibrations of the chain, in the case of negligible sag and moving at a constant low speed, can be formulated as follows [8]

$$m \left[ w_{tt}(x,t) + 2v w_{xt}(x,t) + v^2 w_{xx}(x,t) \right] - \left\{ [T_0 + P(t)] w_x(x,t) \right\}_x = f(x,t), \quad (8)$$

where  $m$  is mass per unit length of the chain,  $w(x,t)$  is the chain displacement with  $x$  denoting the spatial coordinate measured along the span,  $T_0$  represents static tension of the chain and  $P$  is a force combining the loads due to the polygonal effects and impacts, and  $f(x,t)$  is an external periodic load originating from the polygon effects. It is evident from Eq. 8 that both the polygonal action load and impact load represent parametric excitations.

The polygonal action load is periodic and depends on the angular speed of the sprocket. Thus, external and parametric resonances may arise in the escalator chain drive. A small excitation due to the polygonal action can produce a large transverse response of the chain when the frequency of the external load becomes close to one of the natural frequencies of the chain. When the frequency of the parametric excitation is near twice one of the natural frequencies of the chain the *principal parametric resonance* results [9,10].

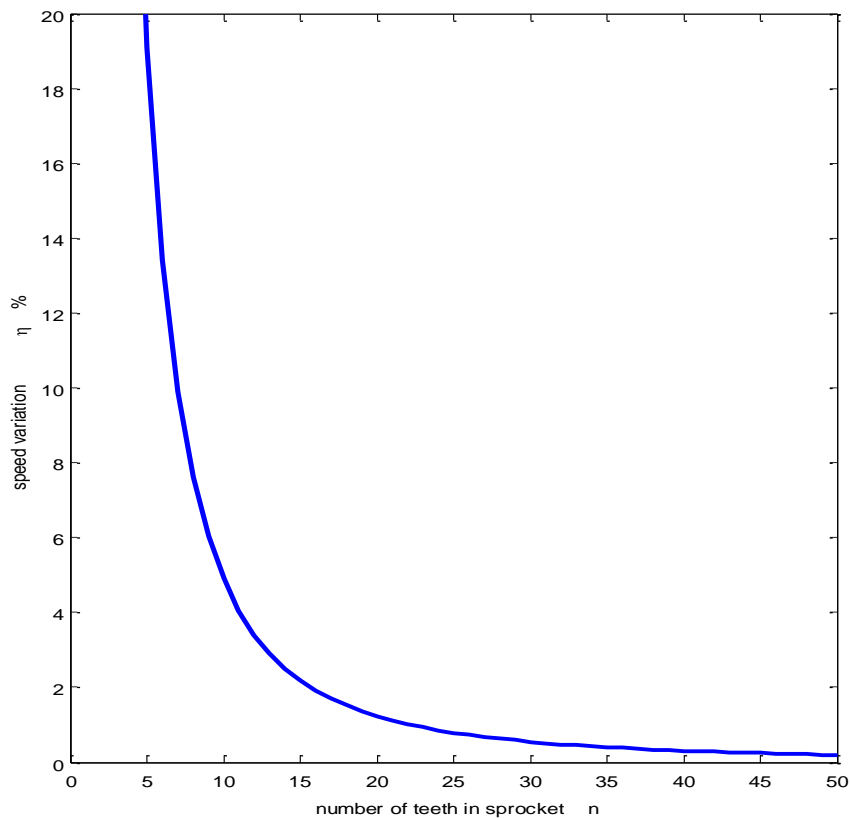


Figure 7. Ratio of speed fluctuation.

## VIBRATION SUPPRESSION

Passive and active vibration control and suppression techniques can be employed in lift and escalator systems. The main passive methods used to suppress and mitigate the effects of excessive vibrations include the following:

- the control of the natural frequencies to avoid resonance under external excitations;
- the use of viscoelastic materials (viscoelastic damping treatment) to dissipate vibrational energy and to prevent excessive response of the system;
- the use of vibration isolators to reduce the transmission of excitation from one part of the machine to another;
- the application of an auxiliary mass neutralizer or vibration absorber to reduce the response of system.

In lift systems vibration isolation is often applied. The lift car is mounted within the sling structure on elastomeric isolation pads to reduce vibration transmission to passengers. In the machine system mounted on steel beams/frame and supported by a concrete floor vibration isolation pads are inserted between the machine/frame and frame/floor to reduce the transmission of excitation forces and vibration to the suspension/car system. The car roller guides are equipped with spring-damper elements to suppress vibration due to the rail excitation sources.

Various passive methods of suppressing chain vibrations in escalator systems have been proposed. The fundamental approach is to reduce the speed fluctuations by the application of chain guide rails of various designs [11,12].

Alternatively, active vibration control (AVC) techniques, that involve actuators to generate forces and to apply them to the structure/machine in order to reduce its dynamic response, can be

employed. The fundamental principle of AVC is illustrated in Fig. 8. The vibration (response)  $x$  of the machine of mass  $m$  is measured using a motion sensor. The response is then used to determine the force to apply to the machine via the actuator (hydraulic or piezoelectric device or an electric motor). The mathematical algorithm to calculate the force is called the *control law*. The system comprising the sensor, actuator and the electronic circuit to read the sensor's output and determine and supply the required signal to the actuator is referred to as *feedback control system*.

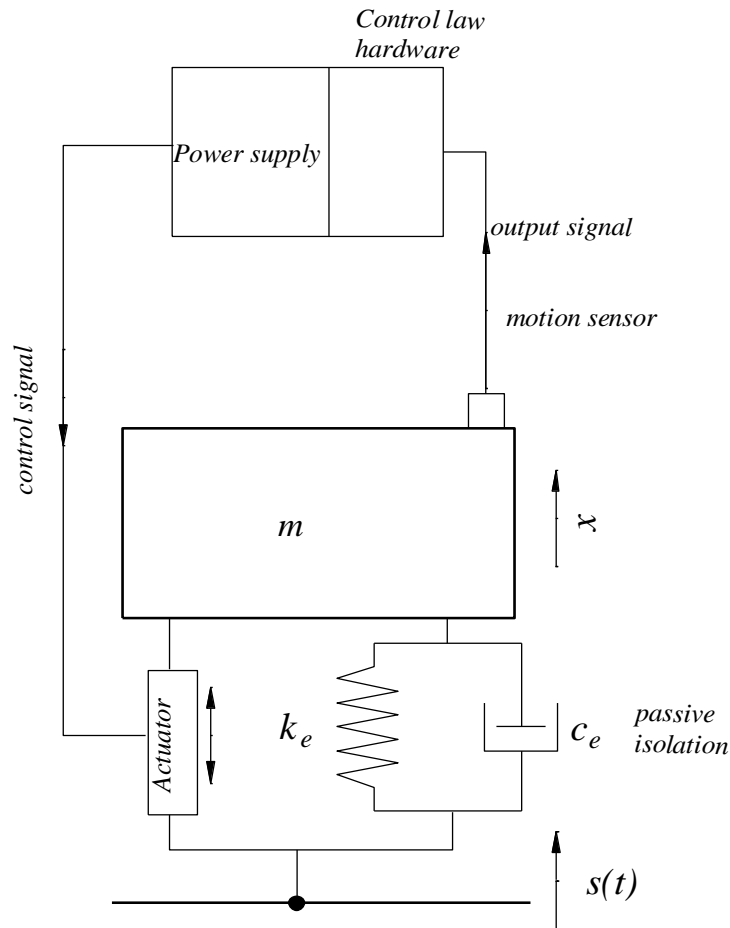


Figure 8. Active vibration control.

In lift systems this method has been used to develop *active roller guides* (ARG) to reduce the horizontal vibrations of lift car caused by guide rail excitation in high-speed, high-rise applications. Also, *active vibration dampers* can be applied under the car, between its floor and sling, to suppress vertical vibrations [13].

## CONCLUSIONS

Vibration phenomena in lift and escalator systems lead to poor ride quality. Eccentric pulleys and sheaves, systematic resonance in the electronic control system, and gear and motor generated vibrations are typical causes of vertical vibrations of a lift car. Uneven, bent rails, incorrect installation and rough surface cause horizontal vibration of the car and of its suspension members. Escalators and moving walks are chain-driven and the chain is a major source of vibration. Passive and active vibration suppression techniques can be used to control vibration phenomena. The latest techniques in the AVC technology can be adopted to mitigate the effects of vibrations and deployed to control adverse dynamic behaviour of lift and escalator systems.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Derivation of an Elevator Round Trip Time Formula under Up-peak Traffic for the Case of Four Special Conditions

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**Abstract.** The design of vertical transportation systems still heavily relies on the calculation of the round trip time ( $\tau$ ). The round trip time ( $\tau$ ) is defined as the average time taken by an elevator to complete a full trip around a building. There are currently two methods for calculating the round trip time: the conventional analytical calculation method; and the Monte Carlo simulation method.

The conventional analytical method is based on calculating the expected number of stops and the expected highest reversal floor and then substituting the values in the main formula for the round trip time. This method makes some assumptions as to the existence of some special conditions (such as equal floor heights and a single entrance). Where these assumptions are not true in a building, this invalidates the use of the analytical formula the use of which will lead to errors in the result. The conventional analytical equation can be further developed to cover some of the special conditions in the building, but they do not cover all of these special conditions and also do not cover combinations of these special conditions.

The simplest round trip time equation makes the following assumptions: equal floor heights, one single entrance, equal floor populations and that the rated speed is attained in one floor jump. The case of unequal floor populations can be accounted for by amending the values of the probable number of stops and the highest reversal by using the formulae for the unequal floor population case.

The work presented in this paper identifies the four special conditions that are assumed in the classical round trip time analytical equation. It then develops analytical formulae for calculating the round trip time equation for any of the four special conditions or any combination of these conditions under incoming traffic conditions.

**Keywords:** Elevator, lift, round trip time, interval, up peak traffic, basement, entrance, sub-entrance, highest reversal floor, probable number of stops, Monte Carlo Simulation, calculation.

### 1. INTRODUCTION

The planning of vertical transportation systems in any building still depends on evaluation of the (round trip time ( $\tau$ )) during the up peak traffic condition (also referred to as the incoming traffic conditions). The round trip time is the time required by an elevator to complete a full cycle in the building.

There are currently two methods for calculating the round trip time in the incoming traffic condition (also known as up-peak). The most widely used method is an analytical one and is based on calculating the expected number of stops and the expected highest reversal floor [1], [2]. The other method recently introduced relies on the use of Monte Carlo simulation in order to arrive at the value of the round trip time, without the need to use formulae that are derived from first probability principles [7]. It is important to note that the work in this paper assumes incoming traffic conditions (i.e., up peak traffic conditions).

In order to derive a general formula for calculating the elevator round trip time it is necessary to study the movement of the elevator car around the building in a single trip during up peak traffic conditions. The round trip time comprises the following components:

1. The door time: The time required for the elevator doors to open and close during every stop.
2. The passenger transfer time: This is the time required by the passengers to board the elevator and alight.
3. The up travelling time: This is the time required by the elevator to travel upwards between floors.
4. The down travelling time: This is the time required by the elevator to express back from the highest reversal floor back to the main terminal.

Figure 1 shows in a diagrammatic form the movement of the elevator car during a round trip, where the  $x$ -axis represents time, the  $y$ -axis represents vertical position within the building.

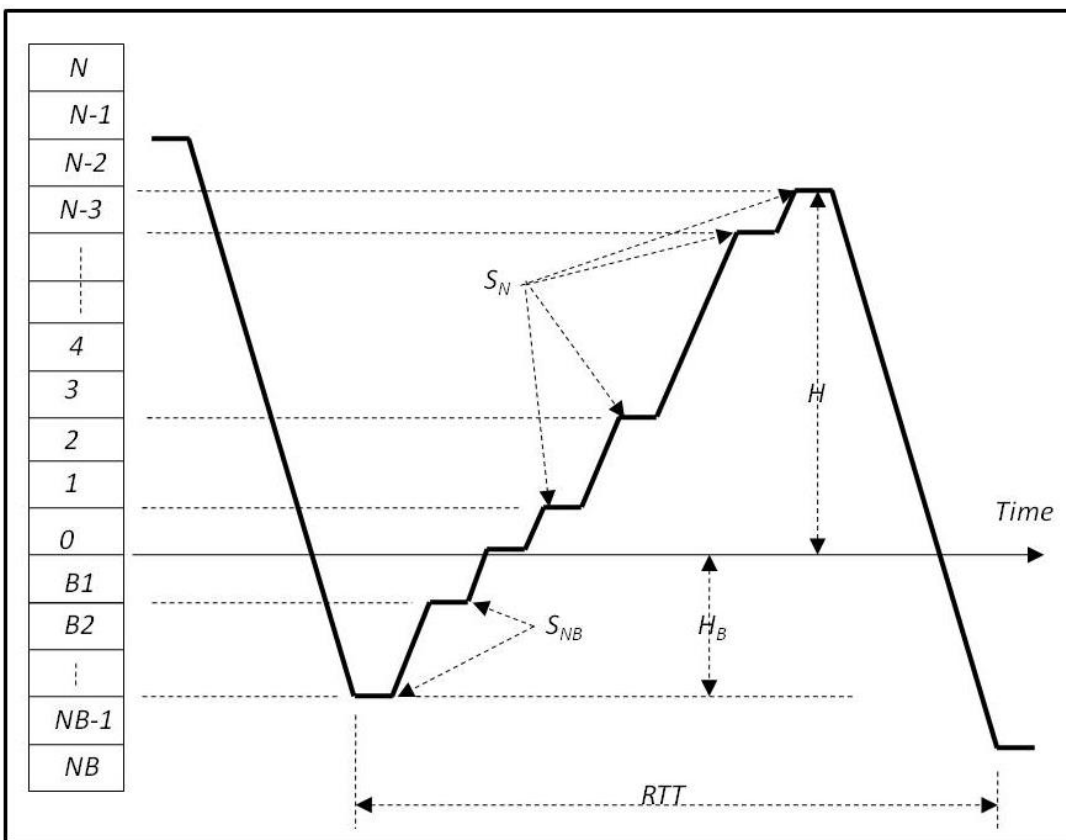


Figure 1: Round trip time timeline where the elevator goes down to the basement.

In describing the types of traffic prevailing in the building, the following three terms will be used:

- Incoming traffic: It describes the traffic entering the building (i.e., all journeys originate at an entrance/exit floor).
- Outgoing traffic: It describes the traffic leaving the building (i.e., all journeys terminate at an entrance/exit floor).
- Inter-floor traffic: This term describes the traffic that circulates within the building (in other words all inter-floor traffic journeys do not originate or terminate at a building entrance floor).

It is convenient to use the classification above in order to describe the prevailing traffic pattern in a building at any point in time. So the prevailing traffic at any one point in time can be described as a mixture of 40% incoming traffic, 40% outgoing traffic and 20% interfloor traffic for example. This is a suitable method of characterizing different traffic patterns at different times of the day in an office building.

Section 2 of this paper reviews the classical analytical method of calculating the round trip time. Section 3 reviews previous work in the area of evaluating the value of the round trip time. Section 4 derives a new equation for the effective floor height when the floor heights are not equal. Section 5 derives the round trip time equation in two stages: the first stage derives it for the case of a single entrance; the second stage adds the condition of multiple entrances. A practical numerical example is given in section 6. Conclusions are drawn in section 7.

## 2. THE CLASSICAL METHOD OF CALCULATING OF THE ROUND TRIP TIME

The traditional method used in the design of vertical transportation systems depends on calculation of the round trip time for an elevator during incoming traffic conditions (usually referred to as up peak traffic). Up peak means that all traffic in the building is incoming, and that the elevator collects  $P$  of the passengers from the main entrance (usually the ground floor), and then moves in the up direction to deliver them to their destination floors.

The round trip time ( $\tau$ ) is the time taken by the elevator to collect  $P$  passengers from the main entrance and get them to their destination floors and return again to the main entrance. The actual value of the round trip time can be determined by finding the expected value of the number of stops ( $S$ ) that the elevator will make during its service to the passengers and the expected value of the highest reversal floor ( $H$ ) that the elevator will attain during its journey in the up direction. These two variables (i.e.,  $S$  and  $H$ ) are dependent on the number of floors above the main terminal,  $N$ , and the number of passengers boarding the elevator from the main terminal,  $P$ . The kinematics of the elevator in moving between floors is based on the rated speed, rated acceleration and rated jerk values.

The value of the round trip time ( $\tau$ ) for an elevator during up peak conditions can be calculated as follows [1], [2] and [4]:

$$\tau = 2 \cdot H \cdot \left( \frac{d_f}{v} \right) + (S + 1) \cdot \left( t_f - \frac{d_f}{v} + t_{do} + t_{dc} + t_{sd} - t_{ao} \right) + P(t_{pi} + t_{po}) \quad (1)$$

where:

$\tau$  is the round trip time in s

$H$  is the highest reversal floor (where floors are numbered 0, 1, 2... $N$ )

$S$  is the probable number of stops (not including the stop at the ground floor)

$d_f$  is the typical height of one floor in metres

$v$  is the rated speed in metres per second

$t_f$  is the time taken to complete a one floor journey in seconds

$P$  is the number of passengers in the car when it leaves the ground floor

$t_{do}$  is the door opening time in seconds

$t_{dc}$  is the door closing time in seconds

$t_{sd}$  is the motor start delay in seconds

$t_{ao}$  is the door advance opening time in seconds (where the door starts opening before the car comes to a complete standstill)

$t_{pi}$  is the passenger boarding time in seconds

$t_{po}$  is the passenger alighting time in seconds

The probable number of stops  $S$  for equal floor populations was first derived in [5]. It can be calculated as follows for equal floor populations:



$$S = N \left( 1 - \left( 1 - \frac{1}{N} \right)^P \right) \quad (2)$$

The highest reversal floor  $H$  was first derived in [6]. It can be calculated as follows for equal floor populations:

$$H = N - \sum_{i=1}^{N-1} \left( \frac{i}{N} \right)^P \quad (3)$$

The flight time between floors at any rated speed, acceleration, jerk and travel distance, can be calculated using the formulae in [7], reproduced below:

(a) Where the elevator attains rated speed in the journey:

$$\text{if } d \geq \frac{a^2 v + v^2 j}{ja} \text{ then } t = \frac{d}{v} + \frac{a}{j} + \frac{v}{a} \quad (4)$$

(b) Where the elevator attains rated acceleration in the journey but does not attain rated speed:

$$\text{if } \frac{2a^3}{j^2} \leq d < \frac{a^2 v + v^2 j}{ja} \text{ then } t = \frac{a}{j} + \frac{\sqrt{a^3 + 4dj^2}}{\sqrt{aj}} \quad (5)$$

(c) Where the elevator attains neither rated acceleration nor speed in the journey:

$$\text{if } d < \frac{2a^3}{j^2} \text{ then } t = \left( \frac{32d}{j} \right)^{\frac{1}{3}} \quad (6)$$

where:

$t$  is the time taken to complete the journey in s

$d$  is the distance of the journey in m

$v$  is the rated speed in  $\text{m}\cdot\text{s}^{-1}$

$a$  is the rated acceleration in  $\text{m}\cdot\text{s}^{-2}$

$j$  is the rated jerk in  $\text{m}\cdot\text{s}^{-3}$

### 3. PREVIOUS WORK

Previous work has introduced enhancements to the round trip time calculation methodology in order to deal with special conditions. These are described in the next three sub-sections.

#### 3.1 Unequal Floor Populations

The case of unequal floor populations is dealt with by amending the formulae for calculating the probable number of stops,  $S$ , and the highest reversal floor,  $H$ . The formulae for the case of unequal floor populations are shown below from [5] and [6] respectively:

$$S = N - \sum_{i=1}^N \left(1 - \frac{U_i}{U}\right)^P \quad (7)$$

$$H = N - \sum_{j=1}^{N-1} \left(\sum_{i=1}^j \frac{U_i}{U}\right)^P \quad (8)$$

Where:

$U_i$  is the population of the  $i^{th}$  floor

$U$  is the total building population

### 3.2 Top Speed Not Attained in One Floor Journey

The case where the top speed is not attained in one floor journey has been dealt with in [9]. It is based on the assumption that all floor heights being equal and a single entrance. It derives a formula for the expected number of one floor journeys during a round trip time, two floor journeys, three floor journeys...*etc.* By multiplying the time taken for each journey length by its probability during a round trip the upward travelling time during the round trip time is calculated.

The formula for a journey of  $r$  floors is reproduced below using different notation:

$$J_r \Big|_{1 \leq r \leq N} = \left( \sum_{i=1}^{N-(r-1)} \left( \left(1 - \sum_{k=i}^{i+(r-2)} P_k\right)^P - \left(1 - \sum_{k=i}^{i+(r-1)} P_k\right)^P \right) \right) - \left( \sum_{i=1}^{N-r} \left( \left(1 - \sum_{k=i}^{i+(r-1)} P_k\right)^P - \left(1 - \sum_{k=i}^{i+r} P_k\right)^P \right) \right) \quad (9)$$

where  $P_k$  is the building population expressed as a percentage of the building as calculated below:

$$P_k = \frac{U_k}{U} \quad (10)$$

Where:

$J_r$  is the expected number of journeys of length  $r$  floors in any round trip

$P_k$  is the percentage of the population on the  $k^{th}$  floor

$r$  is the journey length in floors

$N$  is the number of floors above the ground floor

### 3.3 Multiple Entrances

The case of multiple entrances has been dealt with by calculating the probability of going to the basement and calculating the extra time incurred when the elevator car goes to the basement [3]. The amended formula is shown below, where it is made up of two parts: the original round trip time element for floors above the main entrance and the extra time required to go to the basement multiplied by the probability of going to the basement.

$$\begin{aligned} \tau = & \left( 2 \cdot H \cdot \left( \frac{d_f}{v} \right) + (S+1) \cdot \left( t_f - \frac{d_f}{v} + t_{do} + t_{dc} + t_{sd} - t_{ao} \right) + P(t_{pi} + t_{po}) \right) \\ & + P(\text{basement}) \cdot \left( 2 \cdot H_B \cdot \left( \frac{d_B}{v} \right) + (S_B) \cdot \left( t_B - \frac{d_B}{v} + t_{do} + t_{dc} + t_{sd} - t_{ao} \right) \right) \end{aligned} \quad (11)$$

where:

$P(\text{basement})$  is the probability of the elevator going to the floors below ground in any one round trip.

$d_B$  is the floor height of the basement floors in m  
 $t_B$  is the time to traverse one basement floor in s  
 $S_B$  is the expected number of stops in the basement  
 $H_B$  is the expected highest reversal floor in the basement

This paper first addresses the fourth special condition: the case of unequal floor heights. This is done in the next section. It then develops a universal formula for the round trip time that can deal with all four conditions combined. This is done in section 5.

#### 4. UNEQUAL FLOOR HEIGHTS FORMULA DERIVATION

In the case where the floor heights are unequal, this will have an effect on the calculation of the round trip time equation. The equation for the round trip time can be amended in order to account for this case as follows.

The effect of the unequal floor heights can be taken into consideration by assuming an effective floor height  $d_{f\text{ eff}}$  that can be inserted into the original round trip time equation in place of  $d_f$ .

The effective floor height  $d_{f\text{ eff}}$  is the expected value of the floor height. The effective floor height is the weighted average of the product of each floor height multiplied by the probability of the elevator passing through that floor. In order for the elevator to pass through a floor it should travel to any of the floors above that floor. Thus it is necessary to find the probability of the elevator travelling above a certain floor,  $i$ .

The probability of the elevator not stopping at a certain floor, assuming equal floor populations is the probability that passenger  $j$  will stop at a floor  $i$ :

$$P(\text{pass } j \text{ will stop at floor } i) = \left( \frac{U_i}{U} \right) \quad (12)$$

where  $N$  is the number of floors above the ground floor. Thus the probability that passenger  $j$  will not stop at a floor  $i$  is:

$$P(\text{pass } j \text{ will NOT stop at floor } i) = \left( 1 - \frac{U_i}{U} \right) \quad (13)$$

But the car contains  $P$  passengers. So the probability that none of them will stop at floor  $i$  is the product of all of their respective probabilities:

$$P(\text{all pass will NOT stop at floor } i) = \left( 1 - \frac{U_i}{U} \right)^P \quad (14)$$

The probability that the lift will not travel any higher than a floor  $i$  is the probability that it will not stop on floor  $i+1$  or  $i+2$  or  $i+3$  all the way to floor  $N$ . This is expressed as the product of these individual probabilities:

$$P(\text{elevator will not travel above floor } i) = \left( 1 - \frac{U_N}{U} \right)^P \cdot \left( 1 - \frac{U_{N-1}}{U - U_N} \right)^P \cdot \left( 1 - \frac{U_{N-2}}{U - U_N - U_{N-1}} \right)^P \cdots \left( 1 - \frac{U_{i+1}}{U - U_N - U_{N-1} \cdots U_{i+2}} \right)^P \quad (15)$$

This can be re-written as:

$P(\text{elevator will not travel above floor } i) =$

$$\left(\frac{U-U_N}{U}\right)^P \cdot \left(\frac{U-U_N-U_{N-1}}{U-U_N}\right)^P \cdot \left(\frac{U-U_N-U_{N-1}-U_{N-2}}{U-U_N-U_{N-1}}\right)^P \cdots \left(\frac{U-U_N-U_{N-1}\cdots-U_{i+2}-U_{i+1}}{U-U_N-U_{N-1}\cdots-U_{i+2}}\right)^P \quad (16)$$

Putting all terms inside the same bracket gives:

$P(\text{elevator will not travel above floor } i) =$

$$\left(\left(\frac{U-U_N}{U}\right) \cdot \left(\frac{U-U_N-U_{N-1}}{U-U_N}\right) \cdot \left(\frac{U-U_N-U_{N-1}-U_{N-2}}{U-U_N-U_{N-1}}\right) \cdots \left(\frac{U-U_N-U_{N-1}\cdots-U_{i+2}-U_{i+1}}{U-U_N-U_{N-1}\cdots-U_{i+2}}\right)\right)^P \quad (17)$$

This simplifies to:

$$P(\text{elevator will not travel above floor } i) = \left(\frac{U-U_N-U_{N-1}\cdots-U_{i+2}-U_{i+1}}{U}\right)^P \quad (18)$$

This can be further simplified to the following expression:

$$\begin{aligned} P(\text{elevator will not travel above floor } i) &= \left(1 - \frac{U_N + U_{N-1} \cdots + U_{i+2} + U_{i+1}}{U}\right)^P \\ &= \left(\frac{U_1 + U_2 \cdots + U_{i-1} + U_i}{U}\right)^P \\ &= \left(\sum_{j=1}^i \frac{U_j}{U}\right)^P \end{aligned} \quad (19)$$

The probability that the lift will travel above floor  $i$  is:

$$P(\text{elevator will travel above floor } i) = \left(1 - \left(\sum_{j=1}^i \frac{U_j}{U}\right)^P\right) \quad (20)$$

There are two special cases worth considering. The first is the case where  $i=N$ . Substituting a value of  $N$  for  $i$  results in the probability of the elevator traversing that floor is zero (this is obvious as the elevator cannot travel above the  $N^{\text{th}}$  floor). The second case is the case where  $i=0$ , where the probability is one. This is also obvious as the elevator will definitely go through the height of the ground floor.

Thus the expected value of the travel distance can be calculated as the weighted average of the various floor heights as follows:

$$E(d_{\text{total}}) = \sum_{i=0}^{N-1} \left( d_f(i) \cdot \left(1 - \left(\sum_{j=1}^i \frac{U_j}{U}\right)^P\right) \right) \quad (21)$$

Where:

$E(d_{\text{total}})$  is the expected value of the distance travelled in the up direction in m.

This variable is a distance and thus it has units of m (rather than floors).

It is worth noting that the summation runs from 0 to  $N-1$  (i.e., rather than 1 to  $N$ ). This is in recognition of the fact that the height of the floor  $N$  is irrelevant as the elevator will never traverse that floor height. The 0 index denotes the fact that the elevator will always traverse the ground floor height.

The expected floor height is obtained by dividing the expected total travel distance by the highest reversal floor,  $H$ . So the equation for the effective floor height can be expressed as shown below:

$$E(d_f) = \frac{\sum_{i=0}^{N-1} \left( d_f(i) \cdot \left( 1 - \left( \sum_{j=1}^i \frac{U_j}{U} \right)^P \right) \right)}{H} \quad (22)$$

Substituting the expression for the highest reversal floor based on the general case of unequal floor population, provides the final expression for the effective floor height unequal floor heights:

$$E(d_f) = \frac{\sum_{i=0}^{N-1} \left( d_f(i) \cdot \left( 1 - \left( \sum_{j=1}^i \frac{U_j}{U} \right)^P \right) \right)}{N - \sum_{k=1}^{N-1} \left( \left( \sum_{j=1}^k \frac{U_j}{U} \right)^P \right)} \quad (23)$$

Where:

$d_f(i)$  is the floor height for floor  $i$  in m

$E(d_f)$  is the expected value of the floor heights (effective floor height) which has units of m/floor

$H$  is the highest reversal floor

$N$  is the number of floors above the main terminal

$P$  is the number of passengers boarding the car from the main terminal

It is important to note that formula (23) is only applicable under incoming traffic conditions.

Having derived the formula for the effective floor height under unequal floor heights as well as unequal floor populations provides a tool to address the issue of unequal floor heights, provided that the top speed is attained in one floor journey. The resulting value from formula (23) can be substituted as the effective floor height in the general round trip time formula shown in (1) in place of  $d_f$ .

## 5. DERIVATION OF THE ROUND TRIP EQUATION FOR THE GENERAL CASE

The last section tackled the special case of the unequal floor heights combined with unequal floor populations. It allowed the calculation of the round trip time where the floor heights are unequal and the floor populations are unequal for a building with a single entrance. However, it cannot be used in the case where the top speed is not attained in one floor journey.

In this section, the round trip time formula is derived for the case where the top speed is not attained in one floor journey, where the floor heights are unequal and where the floor populations are unequal for a building with multiple entrances.

The first subsection derives the formula for the round trip time under the first three special conditions (top speed not attained, unequal floor heights and unequal floor populations). The second subsection amends the formula to cover the case for multiple entrances.

### 5.1 Floor round trip time equation derivation assuming a single entrance

In order to develop the universal round trip equation, it is necessary to subdivide the round trip time in a way different to that previously followed. For the purposes of this derivation, there are a number of time components that make up the total round trip time as follows:

- a) Passenger boarding and alighting time. This will be denoted as  $t_P$ .
- b) Door closing and opening times. This is repeated a number of times equal to the number of stops plus one stop (for the main entrance). This will be denoted as  $t_D$ .
- c) Time to travel in the upward direction to deliver the  $P$  passengers to the upper floors. This will be denoted as  $t_U$ .
- d) Time to travel back from the highest reversal floor back down the main entrance. This will be denoted as  $t_H$ .

These components are summarized in equation (24) below.

$$\tau = t_U + t_H + t_D + t_P \quad (24)$$

Components a) and b) are stationary time components, while components c) and d) are travelling time components. A full expression for the round trip will be derived below, based on a single entrance.

An office building with  $N$  floors above ground is assumed, where the ground floor is the only entrance to the building. The elevator car fills up with  $P$  passengers on average as it leaves the ground floor. Each of the floors has a population denoted as  $U_k$ , where  $U_k$  is the population of floor  $k$ . Based on the definition above, it is clear that sum of all the populations divided by the total building population is equal to 1 as shown in (25) below.

$$\sum_{k=1}^N \frac{U_k}{U} = 1 \quad (25)$$

The probability of a journey of  $r$  floors starting from the ground floor in the upward direction is [9]:

$$q_{(0)(r)} = \left[ 1 - \sum_{k=1}^{r-1} \frac{U_k}{U} \right]^P - \left[ 1 - \sum_{k=1}^r \frac{U_k}{U} \right]^P \quad (26)$$

Moreover, the probability of a journey of  $r$  floors from floor  $i$  to floor  $j$  can be calculated as shown below (where  $j=i+r$ ):

$$q_{(i)(i+r)} = \left[ 1 - \sum_{k=i+1}^{i+(r-1)} \frac{U_k}{U} \right]^P - \left[ 1 - \sum_{k=i}^{i+(r-1)} \frac{U_k}{U} \right]^P - \left[ 1 - \sum_{k=i+1}^{i+r} \frac{U_k}{U} \right]^P + \left[ 1 - \sum_{k=i}^{i+r} \frac{U_k}{U} \right]^P \quad (27)$$

For each value of  $r$ , there are a number of journeys of length  $r$  floors. Each possible journey of  $r$  floors contributes to the round trip time. Each journey requires a time element that is equal to the time required to travel between the two floors,  $i$  and  $j$ . The contribution of such an element is equal to the product of the probability of the journey taking place and the time this actually takes.

$$t_{r(i)(j)} = q_{(i)(j)} \cdot t_{(i)(j)} \quad (28)$$

For each value of  $r$ , there are two parts: one journey from the ground floor up  $r$  floors and then all other possible journeys of length  $r$  starting from upper floors. So the contribution to the round trip time from each value of  $r$  is the summation of all possible terms:

$$t_r = q_{0r} \cdot t_{0r} + \sum_{i=1}^{N-r} [q_{(i)(i+r)} \cdot t_{(i)(i+r)}] \quad (29)$$

Where  $t_{(i)(i+r)}$  is time required to travel between floors  $i$  and  $i+r$ . This can be calculated based on the distance, rated speed, rated acceleration and rated jerk, using the formulae found in [8]. It is worth noting that  $r$  can vary from the value of 1 (i.e., one floor journey) up the value of  $N$  (i.e., one journey running from the ground floor to the topmost floor covering  $N$  floors). So the total time spent by the elevator travelling in the up direction is the sum of the term in equation (29) over all possible values of  $r$  (1 to  $N$ ).

$$t_U = \sum_{r=1}^N t_r \quad (30)$$

The next step is to calculate the time component  $t_H$ . This is the time required by the elevator to express back from the highest reversal floor back to the ground floor. As the floor heights are not equal, it is not possible to merely multiply the value of the highest reversal floor ( $H$ ) by the floor height.

The total distance that has to be travelled can be found from equation (21), reproduced below.

$$E(d_{total}) = \sum_{i=0}^{N-1} \left( d_f(i) \cdot \left( 1 - \left( \sum_{j=1}^i \frac{U_j}{U} \right)^P \right) \right) \quad (31)$$

Using the kinematic equations ((4), (5) and (6)), the time taken to traverse this distance can be found and is equal to  $t_H$ .

$$t_H = t(E(d_{total})) = t \left( \sum_{i=0}^{N-1} \left( d_f(i) \cdot \left( 1 - \left( \sum_{j=1}^i \frac{U_j}{U} \right)^P \right) \right) \right) \quad (32)$$

where the function  $t(d)$  is the time in s taken to traverse a distance  $d$  based on rated speed, rated acceleration and rated jerk.

The third term,  $t_D$ , in equation (24) represents the door time. The doors will open and close a number of times equal to the expected number of stops plus one (one extra stop is required at the ground floor to load passengers). The calculation of the term requires the calculation of the number of stops,  $S$  and the values of the door opening time, door closing time, motor start delay and the advanced door opening time.

In order to calculate the expected number of stops, the equation below shall be used (which is based on the general assumption of unequal floor populations). It is worth noting that the calculation of  $S$  is not affected by the case of unequal floor heights or the case of top speed not attained in one floor journey.

$$S = N - \sum_{i=1}^N \left[ 1 - \frac{U_i}{U} \right]^P \quad (33)$$

The door time,  $t_D$  can thus be calculated using the formula (34) below:

$$\begin{aligned} t_D &= (S+1) \cdot (t_{do} + t_{dc} + t_{sd} - t_{ao}) \\ &= \left( \left( N - \sum_{i=1}^N \left( 1 - \frac{U_i}{U} \right)^P \right) + 1 \right) \cdot (t_{do} + t_{dc} + t_{sd} - t_{ao}) \end{aligned} \quad (34)$$

The fourth and final term in the round trip time equation represents the passenger boarding and alighting time and is denoted by  $t_P$ . It is easy to calculate by multiplying the number of passengers by the sum of the boarding and alighting time per passenger, as shown below:

$$t_P = P \cdot (t_{pi} + t_{po}) \quad (35)$$

Combining all four equations into the round trip time equation, gives the full equation for the round trip under the three special conditions (unequal floor heights, unequal floor populations and top speed not attained):

$$\tau = \sum_{r=1}^N t_r + t \left( \sum_{i=0}^{N-1} \left( d_f(i) \cdot \left( 1 - \left( \sum_{j=1}^i \frac{U_j}{U} \right)^P \right) \right) \right) + (S+1) \cdot (t_{do} + t_{dc} + t_{sd} - t_{ao}) + P \cdot (t_{pi} + t_{po}) \quad (36)$$

## 5.2 Expansion of the Formula for multiple entrances

In order to account for the effect of multiple entrances, equation (36) is amended in order to allow for the presence of basements, using an approach similar to that in [3].

$$\tau_B = t_{B_D} + t_{D_B} + t_{H_B} \quad (37)$$

where:

$\tau_B$  is the average extra time added to the round trip time of the elevator when the elevator goes to the basement

$t_{BD}$  is the time to travel in the upward direction in the basements to collect the  $P$  passengers.



$t_{DB}$  is the door closing and opening times in the basement floors . This is repeated a number of times equal to the number of stops in the basements floors.  
 $t_{HB}$  is the time to travel down to the basement's highest reversal floor.

Expanding (37) gives:

$$\tau_B = \sum_{r=1}^{N_B} t_{rB} + S_B \cdot t_{Door} + t_{HB} \quad (38)$$

where:

$t_{rB}$  is time taken to traverse a journey of r floors  
 $N_B$  is the number of basement floors  
 $S_B$  is expected number of stops in the basement  
 $t_{Door}$  is the time taken by the doors to complete a full opening/closing cycle

Expanding (38) gives:

$$\tau_B = \sum_{r=1}^{N_B} t_{rB} + S_B \cdot (t_{do} + t_{dc} + t_{sd} - t_{ao}) + t_{HB} \quad (39)$$

The general equation for calculating the universal round trip time in the general case assuming up peak traffic conditions and the presence of basements is shown below:

$$\tau_{GB} = [t_U + t_D + t_H] \times (1 - P_{(basement)}) + [t_U + t_D + t_{B_D} + t_{D_B} + t_{H-H_B}] \times (P_{(basement)}) + t_P \quad (40)$$

$P_{(basement)}$  is the probability that the elevator will go to at least one of the basements (sub-entrances) in a round trip journey (which is equal to the probability of the elevator going to the basement in any one round trip journey). The formula for calculating this probability is shown below:

$$P_{(basement)} = \left[ 1 - \prod_{i=1}^{N_B} (1 - P_{arr}(i))^P \right] \quad (41)$$

## 6. PRACTICAL EXAMPLE

In order to illustrate the application of the equation, a practical example is given and solved below.

An office building has a total of 18 floors: 14 office floors above ground, one ground floor and three car-park basement floors under the ground floor. The floor populations, arrival rates and floor heights are shown in the table below:

**Table 1: Floor heights, population and arrival rates in the building.**

Floor	Floor height (m)	Floor population	Arrival percentage (%)
L14	4	50	-
L13	4	50	-
L12	4	100	-
L11	4	100	-
L10	4.5	100	-
L9	4.5	100	-
L8	4.5	100	-
L7	4.5	100	-
L6	4.5	100	-
L5	4.5	100	-
L4	4.5	100	-
L3	4.5	100	-
L2	4.5	150	-
L1	4.5	150	-
G	5.0	-	85%
B1	3.2	-	5%
B2	3.2	-	5%
B3	3.2	-	5%

The following parameters will be assumed:

**Table 2: Traffic analysis parameters.**

Parameter	Value
Arrival rate	12%
Target interval	30 s
Passengers	16.8
Door opening time	2 s
Door closing time	3 s
Motor start delay	0.5 s
Advanced door opening	0 s
Rated speed	4.0 m·s <sup>-1</sup>
Rated acceleration	1.0 m·s <sup>-2</sup>
Rated jerk	1.0 m·s <sup>-3</sup>
Passenger boarding time	1.2 s
Passenger alighting time	1.2 s

The first step is to calculate the round trip time without the presence of basements. The equation for the round trip time where the only entrance is the ground floor (G) can be written as follows:

$$\tau = t_U + t_H + t_D + t_P \quad (42)$$

Where:

- $\tau$  is the round trip time in s
- $t_U$  is the time to travel in the upward direction to deliver the  $P$  passengers to the upper floors.
- $t_H$  is the time to travel back from the highest reversal floor back down to the main entrance.
- $t_D$  is the door closing and opening times. This is repeated a number of times equal to the number of stops plus one stop (for the main entrance).
- $t_P$  is the passenger boarding and alighting time.

The time to deliver  $P$  passengers in the upward direction to the upper floors can be calculated from equations (29) and (30). This gives the following value:

$$t_U = \sum_{r=1}^N t_r = 57.3941 \text{ s} \quad (43)$$

The expected running time in the down direction  $t_H$  can be found by using the expected value of the total floor heights  $E(d_{total})$  as shown in equation (21):

$$E(d_{total}) = \sum_{i=0}^{N-1} \left( d_f(i) \cdot \left( 1 - \left( \sum_{j=1}^i \frac{U_j}{U} \right)^P \right) \right) \quad (44)$$

$$E(d_{total}) = \left( \begin{aligned} &5 \times \left( 1 - (0)^{16.8} \right) + 4.5 \times \left( 1 - \left( \frac{150}{1400} \right)^{16.8} \right) + 4.5 \times \left( 1 - \left( \frac{150 + 150}{1400} \right)^{16.8} \right) + \\ &4.5 \times \left( 1 - \left( \frac{150 + 150 + 100}{1400} \right)^{16.8} \right) + 4.5 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4.5 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + 4.5 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4.5 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4.5 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4.5 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4.5 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100}{1400} \right)^{16.8} \right) + \\ &4 \times \left( 1 - \left( \frac{150 + 150 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 100 + 50}{1400} \right)^{16.8} \right) \end{aligned} \right) \quad (45)$$

$$E(d_{total}) = 58.28 \text{ m} \quad (46)$$

$$t_H = t(E(d_{total})) = t(58.28) \quad (47)$$

$$t_H = 19.57 \text{ s} \quad (48)$$

Using the value of  $P$  of 16.8 passengers, the probable number of stops  $S$  can be calculated as follows (assuming unequal floor population) using equation (7):

$$S = N - \sum_{i=1}^N \left( 1 - \frac{U_i}{U} \right)^P \quad (49)$$

$$= 14 - \left( \left( 1 - \frac{150}{1400} \right)^{16.8} + \left( 1 - \frac{150}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{100}{1400} \right)^{16.8} + \left( 1 - \frac{50}{1400} \right)^{16.8} + \left( 1 - \frac{50}{1400} \right)^{16.8} \right) \quad (50)$$

$$S = 9.737$$

The door time,  $t_D$  can also be calculated as follows:

$$\begin{aligned} t_D &= (S + 1) \cdot (t_{do} + t_{dc} + t_{sd} - t_{ao}) \\ &= (9.737 + 1) \times (2 + 3 + 0.5 - 0) = 59.05 \text{ s} \end{aligned} \quad (51)$$

The passenger boarding and alighting time, it is easy to calculate, as shown below:

$$t_p = P \cdot (t_{pi} + t_{po}) \quad (52)$$

$$t_p = 16.8 \cdot (1.2 + 1.2) = 40.32 \quad (53)$$

Substituting in the round trip time equation (24) gives:

$$\tau = t_U + t_H + t_D + t_p \quad (54)$$

$$\tau = 57.39 + 19.57 + 59.05 + 40.32 \quad (55)$$

$$\tau = 176.33 \text{ s} \quad (56)$$

Using Monte Carlo simulation (at 10 000 runs) gives a value of the round trip time of 176.377 s. Applying the formulae developed in this paper gives a value for the round trip time of 176.33 s.

The value of the round trip time where the elevator serves the ground and the basements is given as follows:

$$\tau_B = t_{BD} + t_{DB} + t_{HB} \quad (57)$$

Where:

$\tau_B$  is the average additional time added to the round trip time of the elevator where the elevator goes to the basement in every journey

- $t_{BD}$  is the time to travel in the upward direction in the basements to collect the  $P$  passengers.  
 $t_{DB}$  is the door closing and opening times in the basements floors . This is repeated a number of times equal to the number of stops in the basements floors.  
 $t_{HB}$  is the time to travel down to the basement highest reversal floor.

The time to collect  $P$  passengers from basements floors in the upward direction to the main entrance can be calculated from equations (29) and (30).

$$t_{BD} = \sum_{r=1}^{N_B} t_{rB} = 9.9809 \text{ s} \quad (58)$$

Using the value of  $P_B$  passengers originating in the basements, the number of stops in the basements  $S_B$  can be calculated as follows (assuming unequal floor population), which is a reformulation of equation (7) for arrival floors:

$$S_B = N_B - \sum_{i=1}^{N_B} \left(1 - \frac{P_{arr}(i)}{P_{arr}}\right)^{P_B} \quad (59)$$

Where

$S_B$  is the expected number of stops in the basement

$N_B$  is the number of basement floors

$P_B$  is the number of passengers arriving in the basements

$P_{arr}(i)$  is the percentage arrival from the  $i^{th}$  arrival floor

The critical parameter that decides the value of  $S_B$  is  $P_B$  which is the number of passengers that are picked up from the basements. This is decided by the total percentage arrivals from the basement and can be evaluated as follows:

$$P_B = P \cdot \sum_{i=1}^{N_B} P_{arr}(B_i) \quad (60)$$

$$P_B = 16.8 \times (0.05 + 0.05 + 0.05) = 2.52 \quad (61)$$

$$S_B = 3 - \left[ \left(1 - \frac{0.05}{0.15}\right)^{2.52} + \left(1 - \frac{0.05}{0.15}\right)^{2.52} + \left(1 - \frac{0.05}{0.15}\right)^{2.52} \right] \quad (62)$$

$$S_B = 3 - 1.0798 = 1.92 \quad (63)$$

The door time,  $t_{DB}$  can be calculated as follows:

$$\begin{aligned} t_{DB} &= (S_B) \cdot (t_{do} + t_{dc} + t_{sd} - t_{ao}) \\ &= (1.92) \times (2 + 3 + 0.5 - 0) = 10.56 \text{ s} \end{aligned} \quad (64)$$

The expected running time in the down direction  $t_{HB}$  in the basement floor can be found by using the expected value of the total basement heights  $E(d_{B(total)})$  using a modified version of equation (44) for the basements and applying the results from the kinematic equations (4), (5) and (6) as follows:

$$E(d_{B(total)}) = \sum_{i=1}^{N_B} \left( d_B(i) \cdot \left( 1 - \left( \sum_{j=1}^{i-1} \frac{Parr(j)}{Parr} \right)^{P_B} \right) \right) \quad (65)$$

$$E(d_{B(total)}) = \left( 3.2 \times (1 - (0)^{2.52}) + 3.2 \times \left( 1 - \left( \frac{0.05}{0.15} \right)^{2.52} \right) + 3.2 \times \left( 1 - \left( \frac{0.05 + 0.05}{0.15} \right)^{2.52} \right) \right) \quad (66)$$

$$E(d_{B(total)}) = 8.2473 \text{ m} \quad (67)$$

$$t_{HB} = t(E(d_{B(total)})) = t(8.2473) \quad (68)$$

$$t_{HB} = 6.83 \text{ s} \quad (69)$$

The average extra time added to the round trip time of the elevator when the elevator goes to the basement in every journey is:

$$\tau_B = t_{B_D} + t_{D_B} + t_{HB} \quad (70)$$

$$\tau_B = 9.98 + 10.56 + 6.83 = 27.37 \text{ s} \quad (71)$$

The universal round trip time is:

$$\tau_{GB} = [t_U + t_D + t_H] \times (1 - P_{(basement)}) + [t_U + t_D + t_{B_D} + t_{D_B} + t_{H-HB}] \times (P_{(basement)}) + t_P \quad (72)$$

Where  $t_{H-HB}$  is the flight time for the elevator to travel from the effective highest reversal floor ( $H$ ) to the effective highest reversal basement floor ( $H_B$ ) in the down direction, which equals the time needed to pass through distance  $E(d_{B(total)})$  (total effective basement height) and  $E(d_{total})$  (total effective floor height), evaluated using the kinematic equations (4), (5) and (6).

It is evaluated as follows:

$$t_{H-HB} = t(E(d_{total}) + E(d_{B(total)})) \quad (73)$$

$$t_{H-HB} = t(66.52) \quad (74)$$

$$t_{H-HB} = 21.63 \text{ s} \quad (75)$$

The probability that the elevator will go to at least one of the basements (sub-entrances) in a round trip journey is calculated as follows:

$$P_{(basement)} = \left[ 1 - \prod_{i=1}^{N_B} (1 - P_{arr}(i))^P \right] \quad (76)$$

$$P_{(basement)} = [1 - ((1 - 0.05)^{16.8} \times (1 - 0.05)^{16.8} \times (1 - 0.05)^{16.8})] \quad (77)$$

$$P_{(basement)} = 0.925 \quad (78)$$

$$(79)$$

The universal round trip time can thus be calculated using equation (72) as follows:

$$\tau_{GB} = [57.39 + 59.05 + 19.57] \times (1 - 0.925) + [57.39 + 59.05 + 9.98 + 10.56 + 21.63] \times (0.925) + 40.32 \quad (80)$$

$$\tau_{GB} = 197.235 \text{ s} \quad (81)$$

Using Monte Carlo simulation (at 1000 runs) gives a value of the round trip time of 197.165 s. Applying the formulae developed in this paper gives a value for the round trip time of 197.235 s.

It is worth noting that all the four special conditions apply in the case of this building: Top speed not attained in one floor journey, unequal floor heights, unequal floor population and multiple entrances.

## 7. CONCLUSIONS

The widely used equation or the round trip time assumes a number of special conditions, namely: equal floor heights, equal floor populations, top speed attained in one floor journey and single entrance.

In this paper a new formula has been derived in order to address the problem of unequal floor heights. Moreover, a set of equations has been derived in order to deal with all four special conditions combined. A numerical example has been fully worked out in order to find the value of the round trip time. The result was successfully verified using the Monte Carlo simulation method.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Non-linear energy accumulation buffers

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**Abstract** Lift buffers are listed as safety components in Annex IV of EC Directive 96/16/EC on lifts. Requirements for the application and type testing of buffers, including non-linear energy accumulation buffers, are given in EN 81-1. Their function is to limit acceleration levels in the event that either the car or counterweight reaches the ends of the lift well without the normal slowing down having been effective. In this paper, lift car buffering at the bottom of the well is considered.

Of the three types of buffers commonly accepted by the main codes, both linear energy accumulation (spring) and energy dissipation (hydraulic type) buffers are readily analysed in relation to the acceleration levels of persons in the lift car and have had requirements for their application in the main codes for a long time. Non-linear energy accumulation (polyurethane or elastomeric) buffers have had requirements in EN 81 for a shorter time commensurate with the time that these types have been in common use. These, since their buffering forces are highly non-linear with buffer compression, make prediction of the behaviour of the lift car under buffering more difficult. This paper is intended to provide a simple model assessing the behaviour of the lift car once it has impacted non-linear energy accumulation buffer(s).

This model is used with a number of buffer characteristic curves and with a range of loads and buffer impact speeds, both in the free fall and assuming that the suspension remains intact, to examine the likely behaviour of the lift car after contacting the car buffer(s). A further intention is to critically examine both the average and peak accelerations derived from the model in relation to the requirements in EN 81-1.

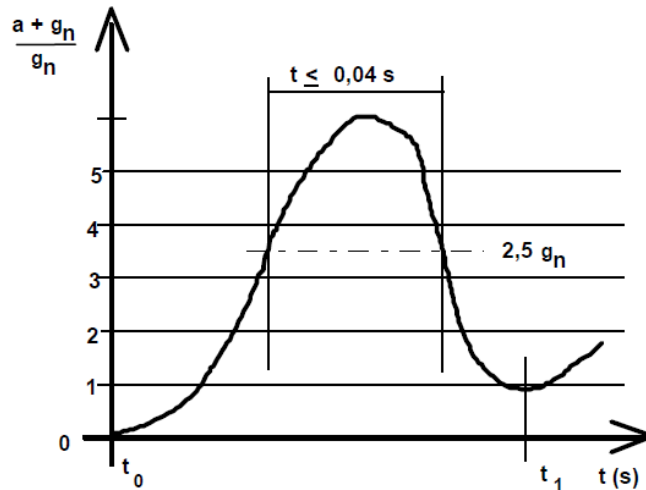
## INTRODUCTION

The requirements in EN 81-1 (BSI, 2010), limiting acceleration for non-linear energy accumulation buffers (typically made from polyurethane and also called elastomeric buffers), are specified in relation to a free falling fully loaded lift car impacting the buffer at 115% of rated lift speed and are for:

- average acceleration to be not greater than  $1 g_n$ ;
- peak acceleration exceeding  $2.5 g_n$  to be for duration not exceeding 40 mS.

EN 81-1 limits the application of non-linear energy accumulation buffers to lifts with rated speeds not greater than 1.0 m/s although further tests have been done with Notified Bodies on their application to lift speeds up to 1.6 m/s.

The requirement for the average acceleration is consistent with the maximum levels set for devices such as progressive safety gear and energy dissipation buffers. The average acceleration, as defined in EN 81-1 Annex F.5 which specifies type testing requirements for non-linear energy accumulation buffers, is measured between the first absolute minimum in the acceleration (on first hitting the buffer) and the second absolute minimum when the car comes momentarily to rest after rebound as shown in figure 1. Type testing of non-linear energy accumulation buffers is used to determine the maximum loads and speeds for a buffer type. Whilst it is clear that buffer impacts are very much more likely to be with the suspension intact, specification of the buffer requirements in this case is very much more problematic for those writing the standards or for the buffer or lift designer. Use of the free-fall fully loaded case provides a consistent basis for carrying out type testing.



$t_0$  = moment of hitting the buffer (first absolute minimum);  
 $t_1$  = second absolute minimum.

**Figure 1 – Figure F.1 from EN 81-1 Annex F – retardation graph**

A requirement limiting acceleration peaks of greater than  $2.5 g_n$  to be no longer than 40 ms for energy dissipation buffers has been in EN 81-1 for some time having been in EN 81-1: 1977 (BSI, 1979) and before that in BS 2655-1 (BSI, 1970). The maximum acceleration of  $2.5 g_n$  for oil dissipation buffers was present in an earlier BS 2655-1 (BSI, 1958) but that did not include for any transient peak exceeding this level. However, none of these standards had requirements for non-linear energy accumulation (polyurethane type) buffers.

Arising from buffering with the suspension intact, there are implications for acceleration levels experienced in the lift car during stops with car loading other than fully loaded. One of the objectives of this paper is to compare the average and peak accelerations with suspension intact using a range of car loads with those of the free fall case.

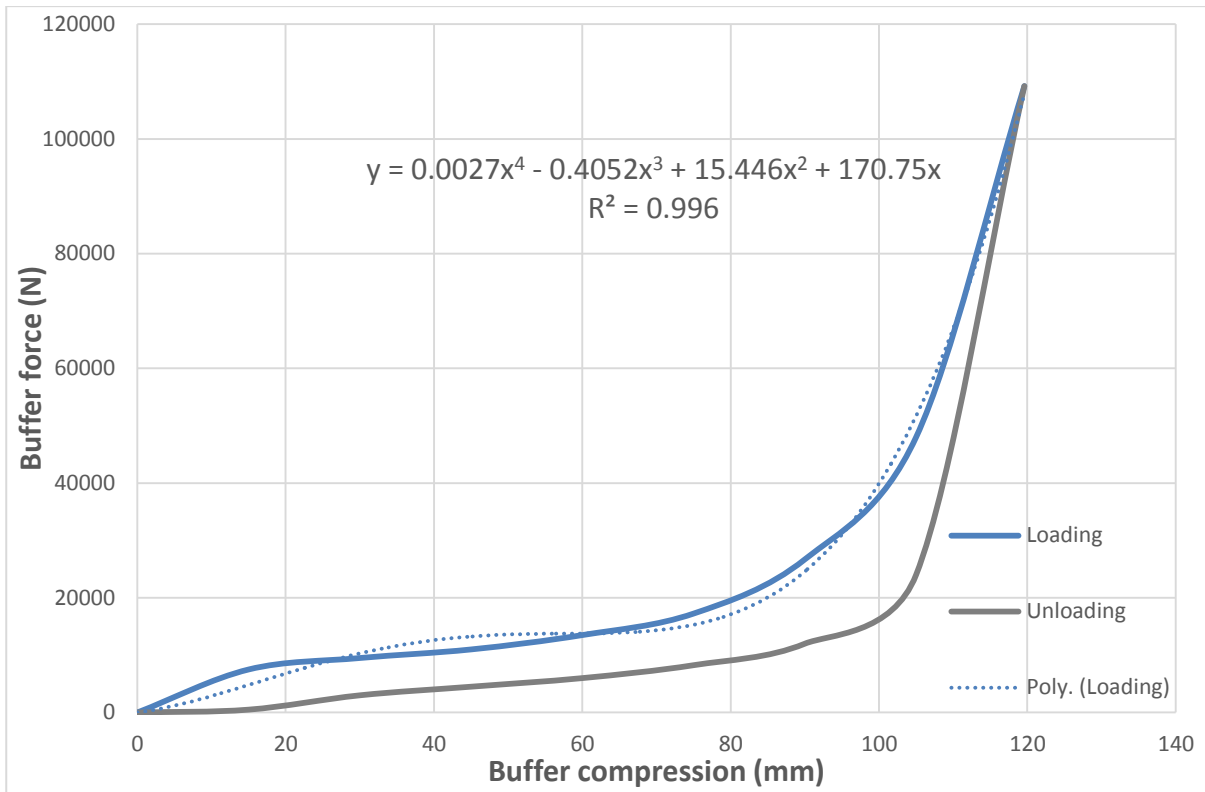
The method to be used to investigate the behaviour of the lift car during buffering with non-linear energy accumulation buffers is through deriving simplified equations of motion and then using these in numerical simulation. This relies heavily on being able to describe the buffering force mathematically as a function of buffer compression.

### **MODELLING NON-LINEAR BUFFER CHARACTERISTIC CURVES**

Typical characteristics of non-linear energy accumulation buffers, as shown in the loading curve in figure 2, show very rapidly increasing forces for compressions greater than 65 – 75% of the buffer height, so the stroke is usually covered up to this range of compression. Below this point, there is a “plateau” area where the buffering force changes much less steeply.

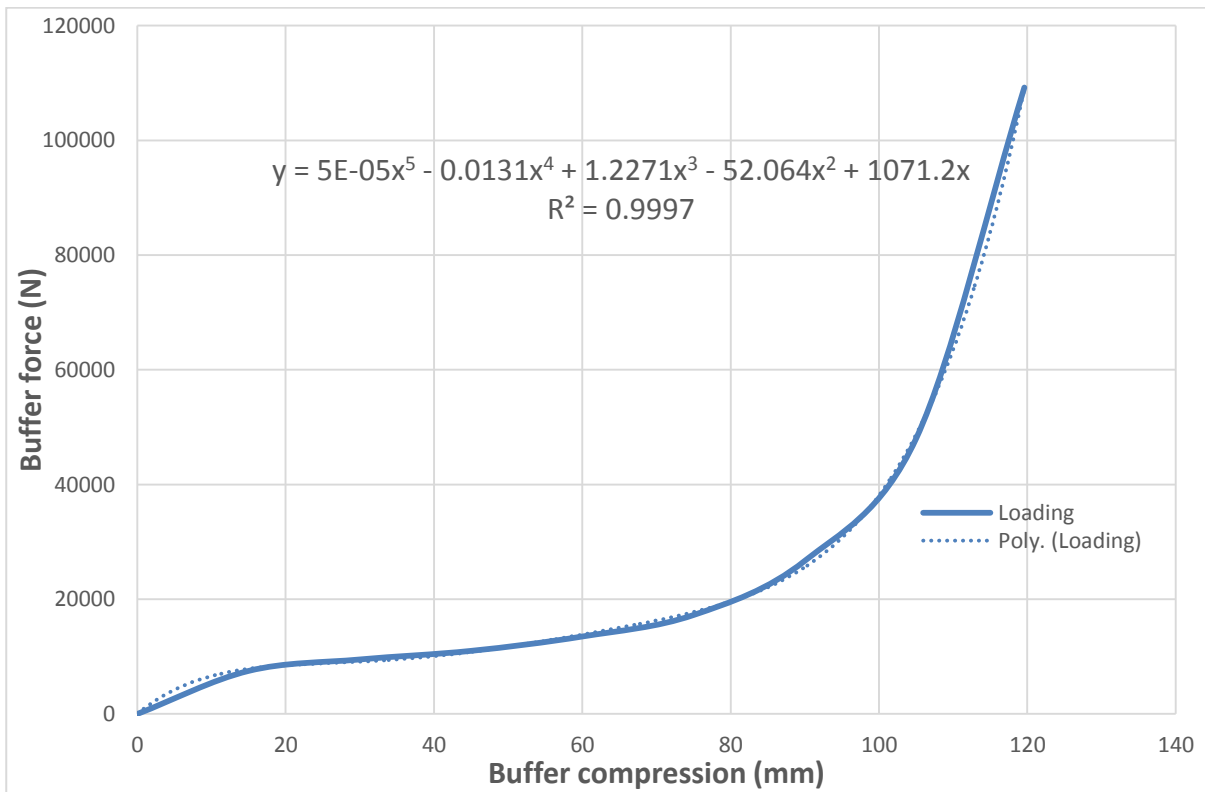
Non-linear buffers exhibit significant hysteresis such that, when the buffer is unloaded, the force is significantly less for a given compression than the force taken to compress the buffer; shown as the unloading curve in figure 2. This characteristic of the material used in these buffers allows them to absorb a significant amount of energy when buffering.

Gill (1997) looked at how the buffer force/ deflection characteristic curves of the type shown in figure 2 could be modelled; reviewing earlier work and concluding that the buffer characteristic curve could be adequately modelled by a fourth order polynomial.



**Figure 2 – Typical non-linear buffer characteristic curve**

A typical buffer characteristic curve and 4<sup>th</sup> order polynomial with line of best fit for the loading curve is shown in figure 2. Gill noted that the best fit would be from using a fifth order polynomial and this is shown in figure 3 below for the same characteristic curve.



**Figure 3: Typical characteristic curve and 5<sup>th</sup> order polynomial fit**

There is useful improvement by using a 5th order polynomial – especially in modelling small compressions, the plateau area and also the steeply rising section as the buffer becomes almost fully compressed.

As part of this work, force/ deflection characteristic curves for 18 buffers from four different manufacturers are considered for a range of rated speeds. The majority of these (16) are for rated speeds up to 1.0 m/s, one for speeds of 1.25 m/s and one for 1.6 m/s. The buffers covered a range of uncompressed heights from 80 mm to 340 mm. To enable comparison between different buffers, the characteristic curves were normalised so that compression was expressed as a proportion of the uncompressed buffer height and force was expressed as a proportion of the buffer force required for a compression of 67% of the buffer’s uncompressed height.

For each buffer, the characteristic curve was first scanned and points for each curve manually selected and entered onto a spreadsheet. Having been normalised as described above, each curve was then fitted with a fourth order polynomial of the form:

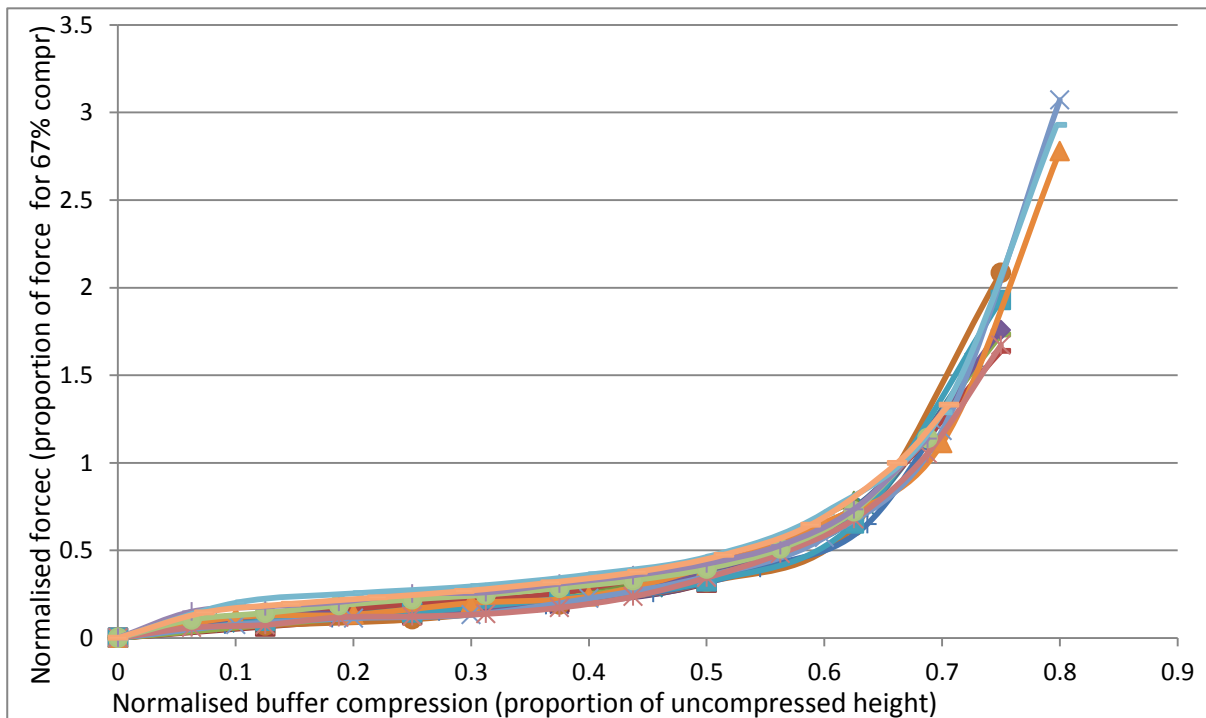
Normalised buffer force:

$$y = A_0 + A_1x + A_2x^2 + A_3x^3 + A_4x^4 \quad (1)$$

where x is the normalised compression (proportion of the uncompressed buffer height).

Although Gill (1997) had allowed a non-zero value of  $A_0$ , in this study  $A_0$  is set at zero to ensure that when  $x = 0, y = 0$ . A measure of how well a fourth order polynomial fits each buffer curve, the values of  $R^2$ , the regression coefficient, were noted; the worst was 0.994 indicating generally very good fits.

All 18 buffer characteristic curves are shown in figure 4. The close bunching of these shows that, irrespective of size or geometry of buffer, manufacturer or type, the buffers studied follow a very similar normalised characteristic curve. This offered the prospect of fitting a curve to all the available data points and to use this for further general investigation.



**Figure 4: normalised buffer characteristic curves for 18 buffers studied**

For the reasons outlined above, a fifth order polynomial was used for this curve fitting and the curve of best fit to all the data points in figure 4 was:

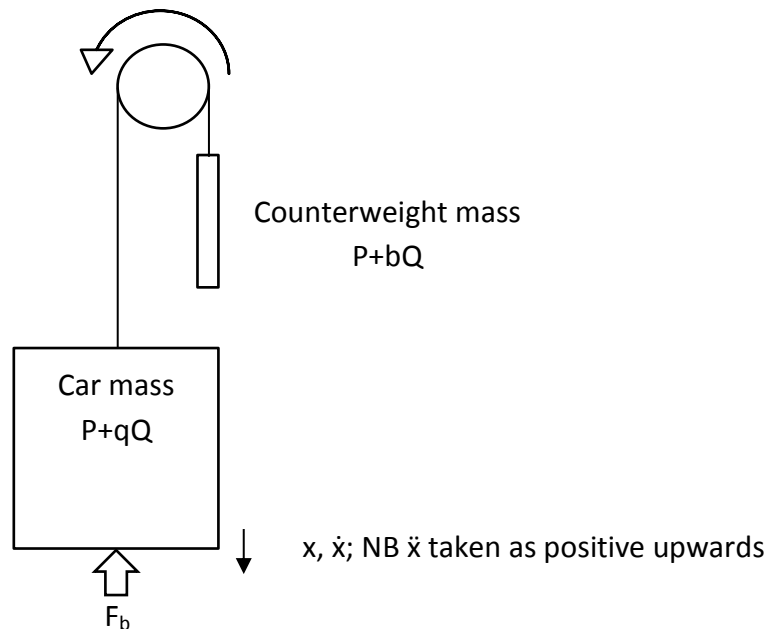
$$y = 2.7124x - 22.309x^2 + 87.249x^3 - 148.16x^4 + 94.62x^5 \quad (2)$$

The regression coefficient  $R^2$  was 0.9873; a useful improvement on 0.98 for the 4<sup>th</sup> order polynomial.

Having a generalised buffer characteristic curve was of benefit because it allowed some general investigation to be done without reference to particular manufacturers or types of buffers and some general conclusions to be drawn.

## ANALYSIS

For a simple analysis, the behaviour of the lift system under buffering can be analysed using Newton's second law since the lift car is influenced by its own mass, the tension if any of elements connecting it to a counterweight, and by the buffering force.



**Figure 5: simplified model of car, counterweight and traction sheave**

Where:

$x$  – deflection of buffer starting from  $x=0$  as the car first touches the buffer (m);

$F_b(x)$  – buffering force for deflection  $x$  (N);

$R_{ct}$  – critical traction ratio for suspension elements over the traction sheave;

$P$  – empty car weight (kg);

$Q$  – rated load of the car (kg);

$b$  – counterweight balance as a proportion of rated load;

$q$  – proportion of car load as a proportion of rated load;

From figure 5, the motion of each of the car and counterweight can be described by:

$$\ddot{x} = \frac{F_b(x) + g_n \{P(R_{ct}-1) + Q(bR_{ct}-q)\}}{P(R_{ct}+1) + Q(bR_{ct}+q)} \text{ for } \ddot{x} \leq 1g_n \quad (3)$$

$$\ddot{x}_{car} = \frac{F_b(x) - g_n(P+qQ)}{(P+qQ)} \text{ for } \ddot{x} > 1g_n \quad (4)$$

$$\ddot{x}_{cwt} = 1g_n \text{ for } \ddot{x} > 1g_n \quad (5)$$

These would be relatively easy to solve analytically if  $F_b(x)$  is a linear function of buffer compression,  $x$ . As demonstrated by the discussion of characteristic curves above, the relationship between buffer force and compression is highly non-linear over its stroke.

Fortunately, the use of numerical simulation allows for the behaviour of such systems to be investigated along with factors which might otherwise be neglected in an analytical approach. To achieve the objectives of this paper, it is necessary to present a simple model for numerical simulation. The model used includes the following:

- formula (3) for when the system remains coupled and acceleration is  $< 1g_n$ ;
- formulae (4) and (5) for the car and counterweight for when car acceleration is  $\geq 1g_n$ ;
- buffer reaction force modelled as a polynomial curve of best fit.

This simplified analysis makes a number of assumptions:

- The influence of the traction sheave and machine on rope tensions during the buffering stop is ignored by assuming that the electromechanical brake does not engage and that, by making  $R_{ct}=1$ , in the equation (3), the tensions are the same on either side of the traction sheave i.e. no effects from either inertia or drive from the machine. This would be most appropriate for a low inertia machine such as a gearless machine.
- Guide friction forces and others due to friction losses in ropes, pulleys etc. are ignored. The influence of these would typically be a few percent of the out of balance load of the lift and therefore a smaller proportion compared with the average buffering force of  $2g_n(P+Q)$ .
- Suspension elasticity is ignored. Non-linear energy accumulation buffers are typically used in low rise lifts owing to the limitation on the maximum rated speed and so a maximum travel of 20 m can be used to assess suspension elasticity. At this travel, depending on the rope selected, factor of safety, and the overall design, the elastic rope stretch for one side would be of the order of 10 mm – 12 mm for the ropes and possibly of the order of 15 mm - 20 mm when compression springs are included. These dimensions are much smaller than the buffering distances and are likely to be important as system acceleration approaches  $1g_n$  and in the case that the suspension becomes taught again after a counterweight bounce. Since the latter should not happen until after the end of the initial acceleration peak, it is neglected in this paper.
- Buffer hysteresis is not considered. Buffer hysteresis is significant in modelling the rebound of the lift car during buffering and hence the second part of the acceleration peak. Since rebound speeds, and therefore accelerations, are likely to be reduced, the peak acceleration curve is likely to reduce more quickly with hysteresis effects included. These effects are not included here and would be interesting to model in future work.
- Other dynamic effects such as due to the mass and damping properties of the buffer are not modelled in this paper.

## INVESTIGATION

Having modelled the buffer characteristic curves and set-up a numerical simulation, these were used to investigate the following questions:

1. For the buffers modelled, what average and peak accelerations are predicted for free-fall fully loaded cars, for both minimum and maximum specified loads?
2. For the buffers modelled, how do predicted acceleration rates for buffering with suspension intact (both empty and fully loaded) compare with the free-fall full load case?
3. For the generalised buffer characteristic curve, how do average and peak accelerations predicted vary for varying load and buffer heights?
4. For the generalised buffer characteristic curve, what are the potential implications of the changes to be introduced with EN 81-20 and EN 81-50?

## RESULTS OF THE INVESTIGATION AND DISCUSSION

The results from preliminary simulation and modelling suggest the following results in relation to the questions posed above.

### Peak accelerations of free-falling fully loaded cars

Simulation results for free falling fully loaded cars at the maximum rated speed for buffers and with the maximum specified loads, the peak accelerations were (with the exception of one buffer at  $4.3 g_n$ ) within a range between  $6.9 g_n$  and  $10.7 g_n$ ; with an average for the 17 buffers of  $8.9 g_n$ . The peak accelerations for the minimum specified loads were somewhat lower with an average of  $5.0 g_n$ .

Of the buffers included in the study with rated speeds greater than  $1.0 \text{ m/s}$ , the buffer for  $1.25 \text{ m/s}$  showed similar acceleration rates and peaks as those at  $1.0 \text{ m/s}$ . The buffer with rated speed of  $1.6 \text{ m/s}$  actually showed the lowest peak accelerations, at  $4.3 g_n$ , for maximum specified load ( $2.8 g_n$  at minimum specified load).

As a comparison, the simulation was run with a linear energy accumulation of the stiffest allowed in EN 81-1 (force of  $4g_n(P+Q)$  for a buffer stroke of twice the gravity stopping distance). This showed a peak acceleration of  $2.3 g_n$  i.e. as expected from an analytical approach.

It should be noted that EN 81-1 has no requirements for the level of the peak acceleration; only for its duration. These were generally within  $40 \text{ ms}$  for the maximum rated load cases but, with the minimum rated loads and lower peak accelerations, the peaks often lasted longer than  $40 \text{ ms}$ . However, the simulations were without damping losses included for the rebound behaviour; these would have the effect of slightly shortening the duration of the peak.

### Implication for buffering of lift cars with suspension intact

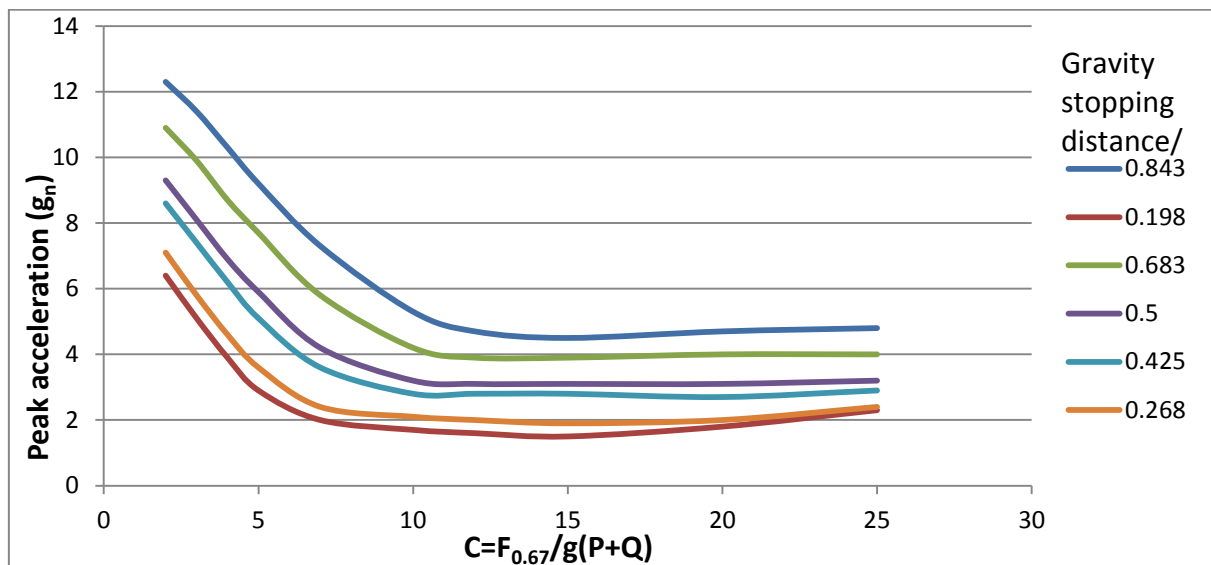
In almost all cases, the peak accelerations with fully loaded car with suspension intact at the maximum specified buffer loads were significantly less than those for the free fall case; with an average of  $6 g_n$ . The peak accelerations for the minimum specified loads were somewhat lower with an average of  $4.5 g_n$ .

Peak accelerations for the empty car case close to the maximum specified buffer load were lower than the fully loaded case at  $4.9 g_n$  average. Where the weight of the empty car was equivalent to the minimum specified load, average peak accelerations were  $4.2 g_n$ . This clear reduction in peak acceleration for the empty car situation runs counter to the expectation of higher accelerations as would be expected during safety gear operation or even on linear energy accumulation buffers.

The explanation for this can be found in the difference in the characteristic of the non-linear buffers since, once onto the steeply increasing part of the curve, relatively small changes in the energy to be absorbed result in significantly different peak buffering forces. Since the empty car situation has significantly less energy to be absorbed compared to the fully loaded cases, the peak buffering force is reduced by more than the reduction in system mass and hence overall acceleration is reduced.

### Variation of average and peak accelerations with load and buffer height

For this investigation, the generalised buffer characteristic curve derived earlier was used to explore how acceleration in the free-fall fully loaded case varied with load and buffer height. It was clear from the investigation of individual buffers that those taller relative to their rated speed showed generally lower peak accelerations. For this reason, the buffer impact speed was normalised by considering the gravity stopping distance for the rated speed as a proportion of the overall buffer height.



**Figure 6: variation in peak acceleration with changes in load and height**

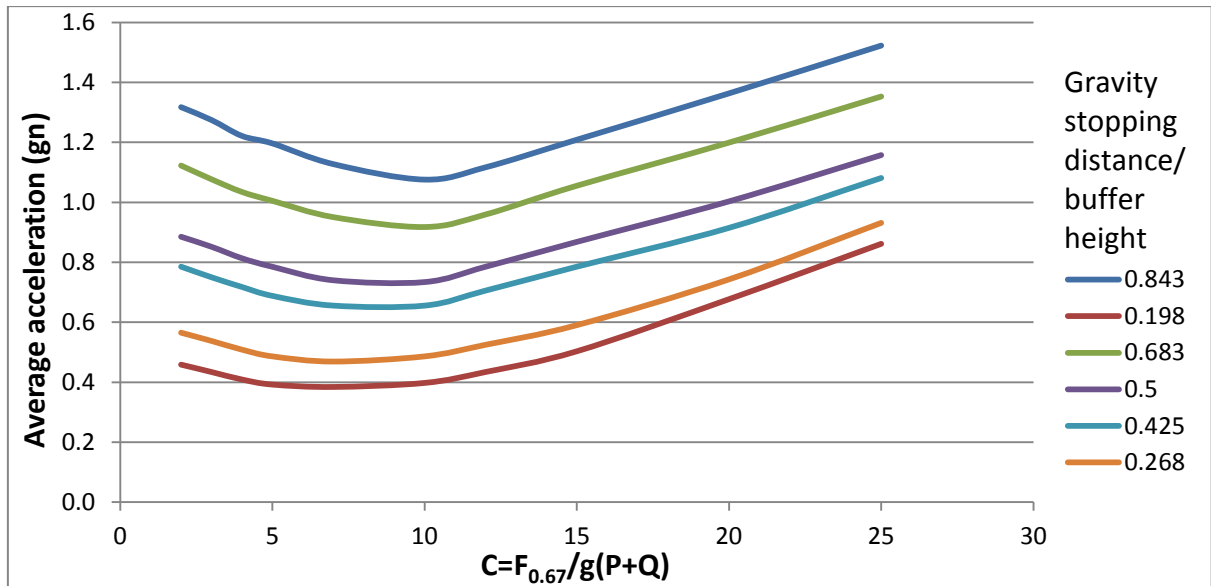
A family of curves was plotted for different proportions of buffer height (equivalent to use of a buffer at different speeds) and these were plotted against variations in the ratio, “C”, between the normalised buffer force (buffer force for compression by 67% of the buffer’s uncompressed height),  $F_{0.67}$ , and the load  $g_n(P+Q)$  in figure 6.

The conclusions from these curves are that, if the value of “C” is small (higher rated load) then the value of peak acceleration is sensitive to the value of “C” and can be reduced significantly by increasing “C” (reducing rated load used). Thereafter, once on the flatter part of the curves, further increasing “C” has no further benefit.

A further observation is that reducing the gravity stopping distance as a proportion of buffer height (so increasing height or reducing rated speed) significantly reduces peak accelerations across the load range.

A similar influence is seen on average accelerations in figure 7; so either increasing buffering height, reducing speed or a combination of these reduces the average acceleration.





**Figure 7: variation in average acceleration with changes in load and height**

The results of figures 6 and 7 effectively demonstrate that there is trade-off in the value of “C” to be selected between the values of peak and average accelerations and that the requirements of meeting limits on each effectively define a working range of loads for given values of buffer height and rated load.

**For the generalised buffer characteristic curve, an investigation of potential implications of the changes to be introduced with EN 81-20 and EN 81-50**

The key new requirement which will be introduced by EN 81-20 will be a limitation of peak acceleration to 6 g<sub>n</sub> for the free-fall fully loaded situation used to specify non-linear buffer requirements.

Reference to the results of individual buffer simulations described above show that, of the 17 buffers simulated, 6 would exceed this limit even at their lowest specified load; 10 would exceed this limit at their maximum specified load; and only one (the buffer with a rated speed of 1.6 m/s) would meet this limit across its specified load range.

It is therefore quite likely that many buffers, where measured peak accelerations exceed 6 g<sub>n</sub> will need to have their load ranges revised. In the cases where this limit was exceeded across the whole load range, it is likely that reduced rated speeds would also be required. It is possible that some buffers might require new type tests.

A new requirement in EN 81-50 for type testing is for a pre-loading of the buffer within 30 minutes of the test to prevent further settlement and deviations during the test. This new requirement is because it has been found that the first impact of the buffer is not generally repeatable yet thereafter the buffer behaves in a reasonably repeatable way.

## CONCLUSIONS

The work on modelling and simulation of the behaviour of the lift car buffering using non-linear energy accumulation buffer(s) allows a number of general conclusions to be drawn:

- The characteristic curves of 18 buffers of different types, manufacturers, heights, load ranges and rated speeds, were modelled by 4<sup>th</sup> and 5<sup>th</sup> order polynomials which provided very good “fits” to the curves.
- The characteristic curves of 17 buffers were used in numerical simulation of buffering of free-falling fully loaded lift cars to provide profiles of acceleration against time. These showed peak accelerations varying across the load ranges for each buffer; at maximum loads, peak accelerations averaged 8.9 g<sub>n</sub> and some being greater than 10g<sub>n</sub>. At the minimum specified loads, the average peak acceleration was 5.0 g<sub>n</sub>.
- A simplified model of the lift masses was used as part of the simulation to investigate peak accelerations with suspension intact and to look at these for fully loaded lift cars at the top of the specified load range and empty cars at the bottom of the load range. In general, the fully loaded case exhibited lower peak accelerations than the free-falling case. The empty car cases showed still further reductions in peak accelerations.
- The characteristic curves for the 18 buffers were normalised for different buffer forces and heights. These showed very good correlation with each other. From these, a general buffer characteristic curve was derived which provided a very good fit and which allowed general investigations and conclusions to be drawn.
- The generalised buffer characteristic curve was used as part of the simulation to derive general graphs showing how peak and average accelerations vary with the specification of the buffer in terms of rated load and also in terms of the rated speed and buffer height. These indicate a load range bounded by meeting the requirements for both average and peak acceleration. These curves provided a basis for assessing how buffers could be brought in line with the new requirement in EN 81-20 to ensure the peak acceleration is not greater than 6 g<sub>n</sub>.

Future work could usefully look at improvements to the results of this study by refining the model used e.g. including suspension elasticity and also by including the effects of buffer hysteresis effects.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Modelling and Simulation of the Dynamic Behaviour of Elevator Systems

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**Keywords:** Modelling, Numerical Simulation, Nonlinear Dynamic Interactions, Lifting Installation, Elevator System

**Abstract.** An elevator represents a multi-body system deployed in buildings to provide vertical transportation. Vibration phenomena taking place in elevator and hoist installations may influence the dynamic performance of their components which in turn may affect ride quality of a lift car. Lateral and longitudinal vibrations of suspension ropes and compensating cables may result in an adverse dynamic behaviour of the entire installation. There is a need to predict the dynamic behaviour of elevator systems under various operating conditions. In particular, it is necessary to predict any possible failures that would require their shutdowns. This paper presents the results of work to develop adequate mechanical models of elevator systems in a multibody simulation software environment. Using these models an analysis can be performed to investigate the influence of design parameters on their performance. Simulation tests have then been carried out and the results are graphically presented through diagrams and animations, for a range of elevator parameters. Conclusions concerning their influence on elevator performance can then be formulated.

### INTRODUCTION

Dynamic simulation of multibody systems plays an important role in a wide range of fields, as in engineering applications, the main goal is to design and manufacture marketable products of high quality. Simulation analysis allows an engineer to simulate the dynamic behaviour of a product. Based on the results, the product design can be optimized prior to actual production. A product may contain mechanical, electrical, or other components. If mechanical components are allowed to move relative to one another, the product is called a multibody (MBD) system [1].

A MBD system is one that consists of solid bodies, or links, that are connected to each other by joints that restrict their relative motion. The study of MBD is the analysis of how mechanisms and systems move under the influence of forces, also known as forward dynamics. A study of the inverse problem, i.e. what forces are necessary to make the mechanical system move in a specific manner is known as inverse dynamics. Motion analysis is important because product design frequently requires an understanding of how multiple moving parts interact with each other and their environment [1,2]. An elevator represents a MBD system deployed in buildings to provide vertical transportation. Vibrations of elevator components may influence the dynamic performance of their components which in turn may affect ride quality of a lift car [3]. This paper presents the theory and MBD simulation results using mechanical models of an elevator system in a multibody simulation software environment. Using these models an analysis can be performed to investigate the influence of design parameters on their performance.

## CASE STUDY

### Theoretical model

A lift car of mass  $P = 1000$  kg is supported by a platform mounted within a sling on elastomeric isolation pads of combined stiffness coefficient  $k_p = 1160$  kN/m as depicted in Fig. 1. The sling mass is  $M = 400$  kg and the car – sling assembly is suspended on 4 steel wire ropes in 1:1 configuration. The ropes are of modulus of elasticity  $E = 0.85 \times 10^5$  N/mm<sup>2</sup>, mass per unit length  $m_r = 0.66$  kg/m, metallic (effective) area  $A_{eff} = 69$  mm<sup>2</sup> (see Table 1). The main propose of this case study is to determine the natural frequencies and modal vectors of the car-sling-rope assembly when the lift is stationary and the length of the ropes at the car side is  $L = 30$  m,.

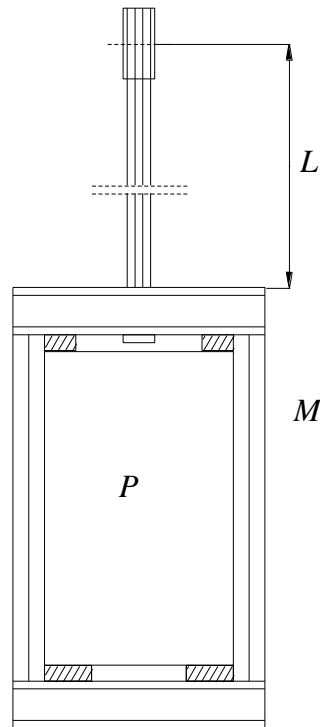


Figure 1. Elevator car-sling assembly and suspension system.

A simplified model of the system is illustrated in Fig. 2. It is evident that the model is essentially equivalent to a 2DOF system. The masses  $M_1$  and  $M_2$ , representing the sling and the car respectively, are constrained by two springs of constants  $k_p$  and  $k_e$  and they can move vertically so that their position is defined by the coordinates  $x_1$  and  $x_2$ , respectively. The equations of free undamped motion of the system given by Eq. 1 - 3 can be derived by the application of Newton's 2nd law [2].

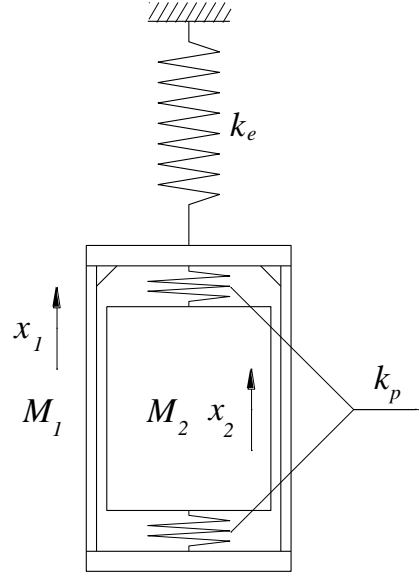


Figure 2. 2DOF model of a lift car – sling – suspension system.

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{0} \quad (1)$$

where

$$\mathbf{M} = \begin{bmatrix} M_e & 0 \\ 0 & M_2 \end{bmatrix} \quad (2)$$

$$\mathbf{K} = \begin{bmatrix} k_e + k_p & -k_p \\ -k_p & k_p \end{bmatrix} \quad (3)$$

represent  $2 \times 2$  symmetric mass and stiffness matrices, where  $n_r$  is the number of suspension ropes. In this formulation the generalized coordinates are assembled in the displacement vector  $\mathbf{x} = [x_1(t), x_2(t)]^T$  and the right hand-side of Eq. 1 is a  $2 \times 1$  zero vector  $\mathbf{0} = [0, 0]^T$ . Assuming  $n_r = 4$  the effective stiffness of the suspension system is

$$k_e = n_r \frac{EA_{eff}}{L} \quad (4)$$

and the equivalent mass of the sling – suspension rope assembly is expressed as:

$$M_e = M_1 + \frac{n_r m_r L}{3} \quad (5)$$

Free undamped vibration of a single degree of freedom (SDOF) system is represented by a harmonic motion. Using the same approach in this model it can argued that the masses  $M_e$  and  $M_2$  move according to

$$\mathbf{x} = \mathbf{X} \cos(\omega t + \varphi); \quad \mathbf{X} = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \quad (6)$$

where  $\omega$  is the natural frequency and  $\mathbf{X}$  represents a vector of modal amplitudes or shapes (the eigenvector). Thus, by assuming that both masses vibrate at the same frequency and are in phase but

have different amplitudes. Such a motion is referred to as synchronous and it is evident that the ratio between the two displacements remains constant throughout the motion so that

$$\frac{X_1}{X_2} = \text{const} \quad (7)$$

Inserting Eq. 6 into equation of motion Eq. 1 the following results

$$(\mathbf{K} - \omega^2 \mathbf{M}) \mathbf{X} = \mathbf{0} \Rightarrow \begin{bmatrix} k_e + k_p - \omega^2 M_e & -k_p \\ -k_p & k_p - \omega^2 M_2 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (8)$$

which represents two simultaneous homogenous algebraic equations in the unknowns  $X_1$  and  $X_2$  with  $\omega^2 \equiv \lambda$  playing the role of a parameter (referred to as an eigenvalue). The problem of finding the values of the parameter  $\lambda$  for which the above equation has a nonzero (nontrivial) solution is referred to as the eigenvalue problem. It is known from linear algebra that the above equation possess a nontrivial solution if the determinant of the coefficient matrix is zero

$$\Delta(\lambda) = \det \begin{bmatrix} k_e + k_p - \omega^2 M_e & -k_p \\ -k_p & k_p - \omega^2 M_2 \end{bmatrix} = 0 \quad (9)$$

Expanding the determinant in equation (11) yields the following characteristic equation (often referred to as frequency equation) for the unknown quantity  $\lambda \equiv \omega^2$

$$\lambda^2 - \left( \frac{k_e + k_p}{M_e} + \frac{k_p}{M_2} \right) \lambda + \frac{k_e k_p}{M_e M_2} = 0 \quad (10)$$

This expression represents a quadratic equation in  $\lambda$  and yields two positive, real roots (eigenvalues) as follows

$$\lambda_{1,2} = \frac{1}{2} \left( \frac{k_e + k_p}{M_e} + \frac{k_p}{M_2} \mp \sqrt{\left( \frac{k_e + k_p}{M_e} + \frac{k_p}{M_2} \right)^2 - 4 \frac{k_e k_p}{M_e M_2}} \right) \quad (11)$$

The corresponding natural frequencies are then found to be  $\omega_{1,2} = \sqrt{\lambda_{1,2}}$ . Thus, there are two vectors of amplitudes (mode shapes or eigenvectors) corresponding to each natural frequency:

$$\begin{aligned} \omega_1 &\Rightarrow \mathbf{X}^{(1)} \\ \omega_2 &\Rightarrow \mathbf{X}^{(2)} \end{aligned} \quad (12)$$

to be determined from the following equations

$$(\mathbf{K} - \omega_1^2 \mathbf{M}) \mathbf{X}^{(1)} = \mathbf{0} \Rightarrow \begin{bmatrix} k_e + k_p - \omega_1^2 M_e & -k_p \\ -k_p & k_p - \omega_1^2 M_2 \end{bmatrix} \begin{bmatrix} X_1^{(1)} \\ X_2^{(1)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (13)$$

$$(\mathbf{K} - \omega_2^2 \mathbf{M}) \mathbf{X}^{(2)} = \mathbf{0} \Rightarrow \begin{bmatrix} k_e + k_p - \omega_2^2 M_e & -k_p \\ -k_p & k_p - \omega_2^2 M_2 \end{bmatrix} \begin{bmatrix} X_1^{(2)} \\ X_2^{(2)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (14)$$

The mode shapes / eigenvectors can be then normalized to satisfy the following condition

$$(\alpha_i \mathbf{X}^{(i)})^T \mathbf{M}(\alpha_i \mathbf{X}^{(i)}) = 1 \Rightarrow \mathbf{Y}^{(i)T} \mathbf{M} \mathbf{Y}^{(i)} = 1 \quad (15)$$

Parameter	Value	Unit
$M_1$	400	kg
$M_2$	1000	kg
$m_r$	0.66	kg/m
$E$	85000	N/mm <sup>2</sup>
$A_{eff}$	69	mm <sup>2</sup>
$n_r$	4	m
$k_p$	1160	kN/m
$L$	30	m

Table 1 Fundamental parameters of the system

$$\omega_1 = 20.0083 \frac{\text{rad}}{\text{s}} (3.1844 \text{ Hz}) \Rightarrow \mathbf{Y}^{(1)} = [-0.0190, -0.0291] \quad (16)$$

$$\omega_2 = 72.8977 \frac{\text{rad}}{\text{s}} (10.4064 \text{ Hz}) \Rightarrow \mathbf{Y}^{(2)} = [-0.0445, 0.0124] \quad (17)$$

The mode shapes are plotted in Figure 3. They illustrate that when the system vibrates in its first mode the amplitude of the second mass is greater than that of the first mass. The motions of the two masses are in phase. When the system vibrates in its second mode the amplitude of the first mass is greater and the magnitudes have opposite signs. Thus, the motions are 180<sup>0</sup> out of phase. It can be noted that one point/ section of the second spring remains stationary at all times; such a point is referred to as a node.

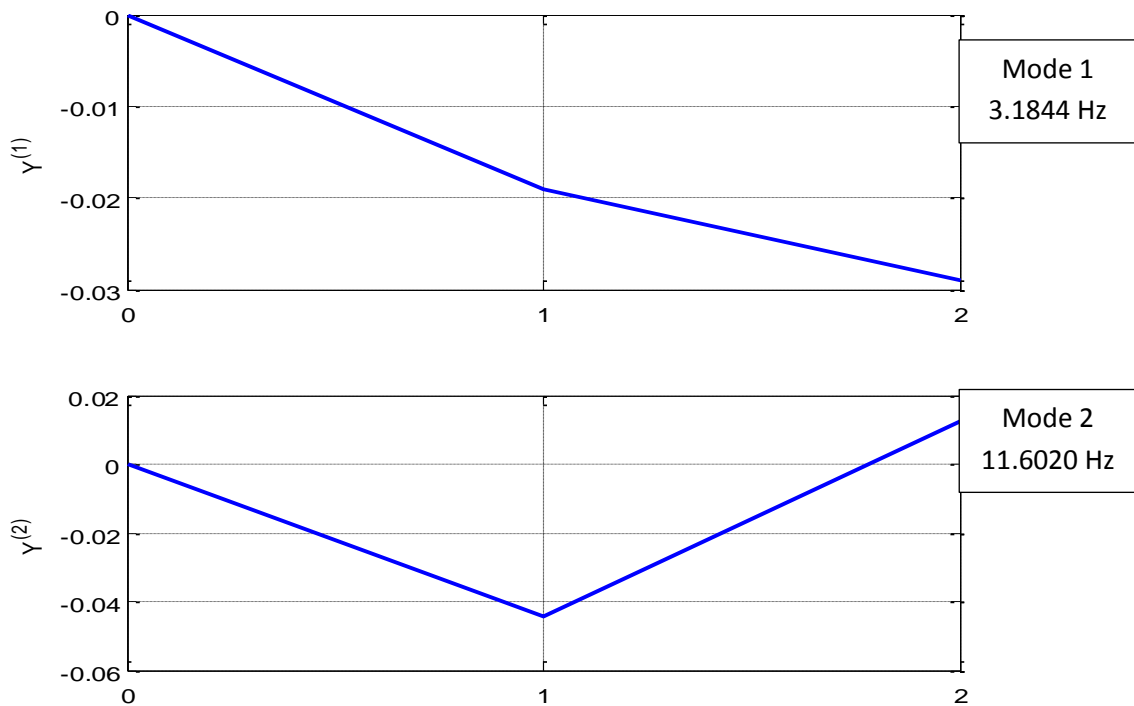


Figure 3. Mode shapes.

It is evident, that in the first mode the sling and the car move in phase. The second (higher) mode is mainly associated with the motion of the sling – suspension rope assembly (with the amplitude of the car close to zero).

### MBD simulation model and results

Using ADAMS/Vibration tools, vibrations of the system represented by the model can be studied. With MBD simulations in ADAMS, physical tests on shakers can be replaced with virtual prototype testing. Noise and vibration are critical factors in the performance of many mechanical designs, with MBD simulation the forced response of a model in the frequency domain over different operating points, evaluate frequency response functions for magnitude and phase characteristics, tabulate contribution of model elements to kinetic, static, and dissipative energy distribution in system modes or animate forced response and individual mode response can be investigated.

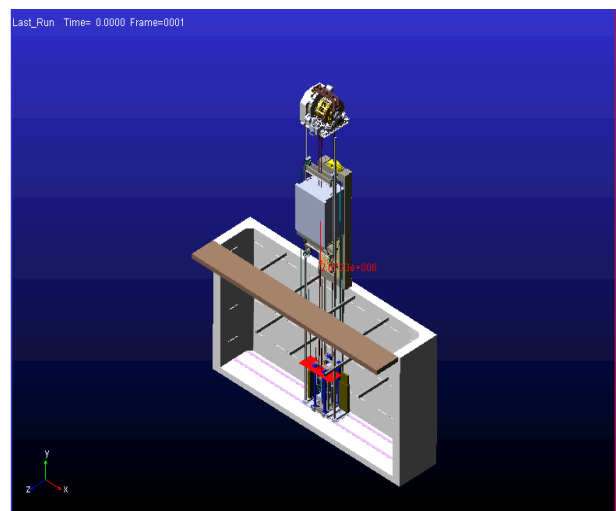
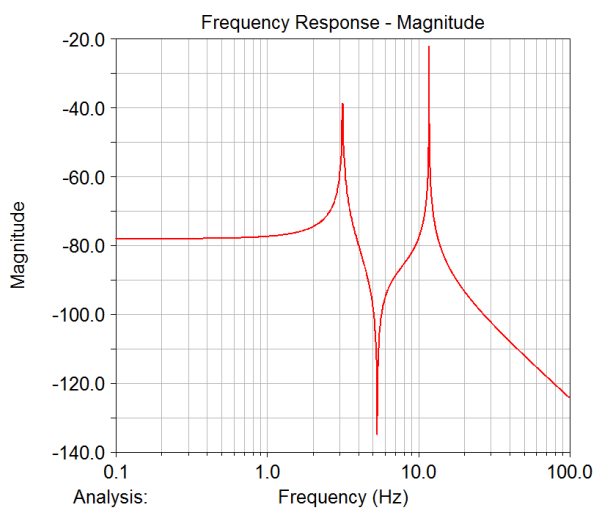




Figure 4. Car-sling-suspension rope simulation model and modes.

Fig. 4 illustrates the usefulness of the solution of the eigenvalue problem. This simulation can demonstrate how the system behaves and helps engineers to associate the natural (resonance) frequencies with the individual components of the system. Fig. 5 and Fig. 6 illustrate the modal behaviour of the car-sling-suspension assembly. The simulation test returns the same numerical values of the natural frequencies and the natural modes as calculated in equations (16-17) and the modal behaviour is illustrated through computer animation. This information is valuable to improve performance and control of any specific mode in order to suppress excessive vibrations in the system.

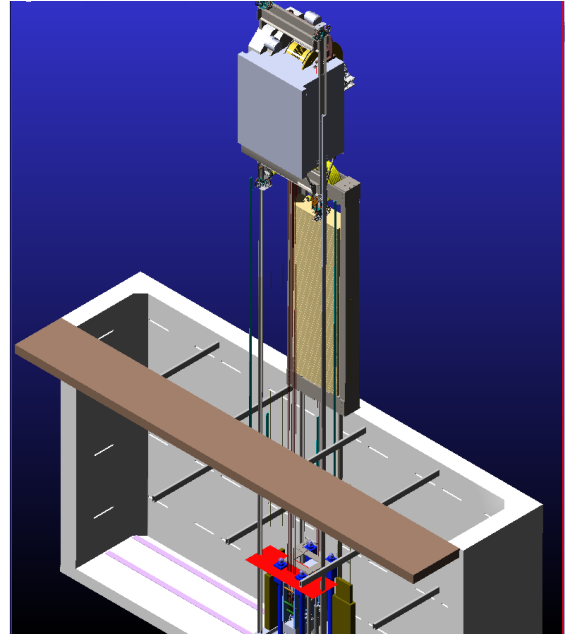
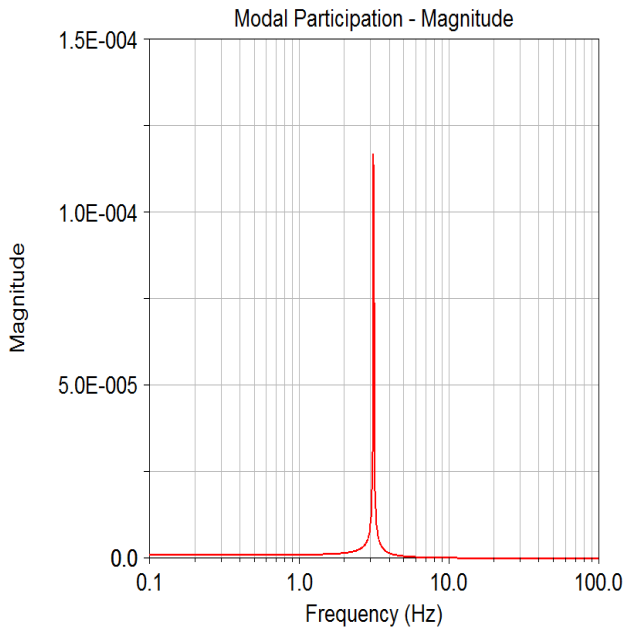


Figure 5. The 1<sup>st</sup> natural frequency and mode simulation and behaviour of the car-sling-suspension MBD system at 3.1844 Hz .

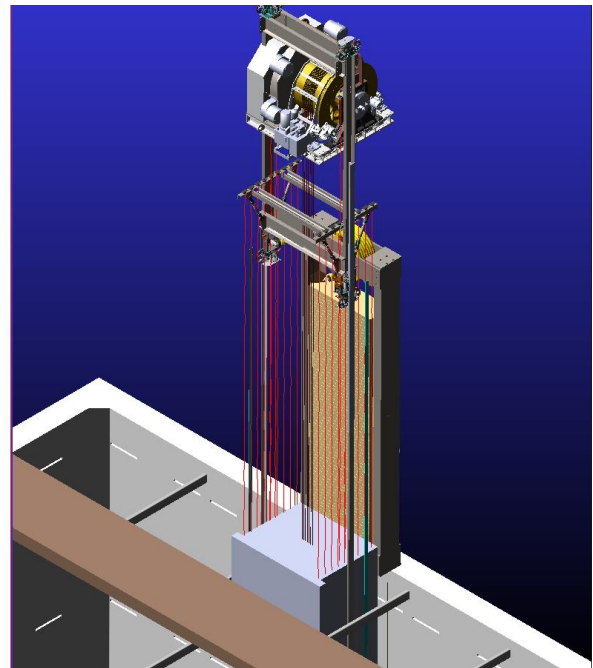
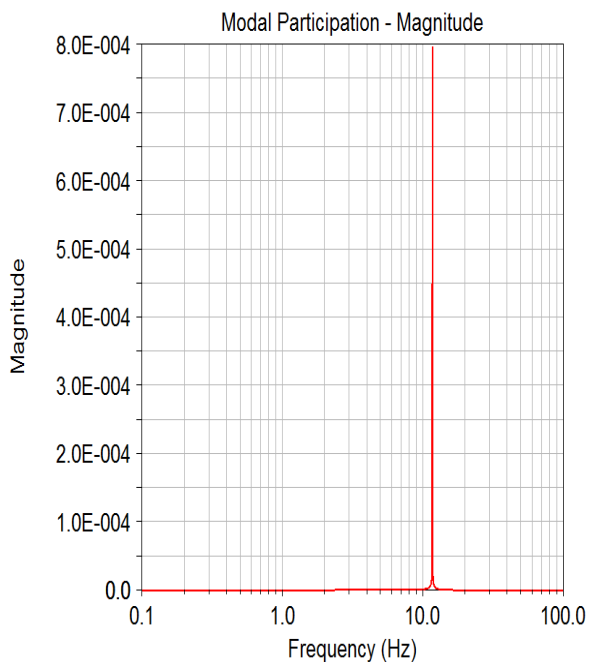


Figure 6. The 2<sup>nd</sup> natural frequency and mode simulation and behaviour of the car-sling-suspension MBD system at 11.6020 Hz

## **CONCLUSION**

An elevator represents a complex MBD system with its dynamic characteristics varying during the travel. MBD modelling and computer simulation techniques can be employed to investigate the dynamic behaviour of the elevator system and its components. However, the models and techniques should be checked through the application of benchmark problem tests and experimental validation so that the models can be used to make predictions with sufficient confidence.

## **ACKNOWLEDGEMENT**

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Application of Linear motor technology for variable speed passenger transportation systems

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**Abstract.** Moving walkways are high capacity continuous systems able to transport people. Their limitation today is the transportation time, due to the speed, to ensure a safe embarking and disembarking of passengers. The potential application of variable speed horizontal continuous systems to improve effectiveness of traditional moving walkways is analyzed in this paper.

Different existing concept alternatives to achieve variable speed are presented, stressing those that are currently open to the public. These solutions are based on mechanical systems that mostly include conventional motors with driving shafts, sprockets, gears, rollers and chain transmissions among others.

This paper gives a general overview of the background, motivation, technical solutions and challenges of variable speed solutions, focusing on the possible application of linear motor technology for the drive elements.

The normative, safety and comfort levels of variable speed transportation systems have to be analyzed under the existing knowledge and regulations of conventional moving walks and their particular aspects such as entry and exit speed, acceleration and jerk rates.

### 1. PRESENT AND FUTURE TRANSPORTATION CHALLENGES AND TRENDS

The twentieth century was characterized by many changes. Urban population increased from approximately 10% up to almost 50% and this trend is still ongoing today (Fig. 1). In 2012 approximately 3700 million people lived in cities and 2050 reports estimate that urban population will increase up to 6300 million representing almost 70% of the total world population. This increase in urban population is due in part to the attractiveness of the cities that arise in the economy, culture and rising living standards. There is a strong link between sustainable urban development and transport. Many cities have grown around the use of the car but this is not a universal transport. Future cities should be accessible and attractive to all residents and visitors. This means that cities must be designed for people, business, security and high quality environment.

Cities are changing, and understanding this evolution and people needs will help to define the future transportation trends. The ultimate goal is the increased use of public transportation to benefit from the economical and ecological advantages.

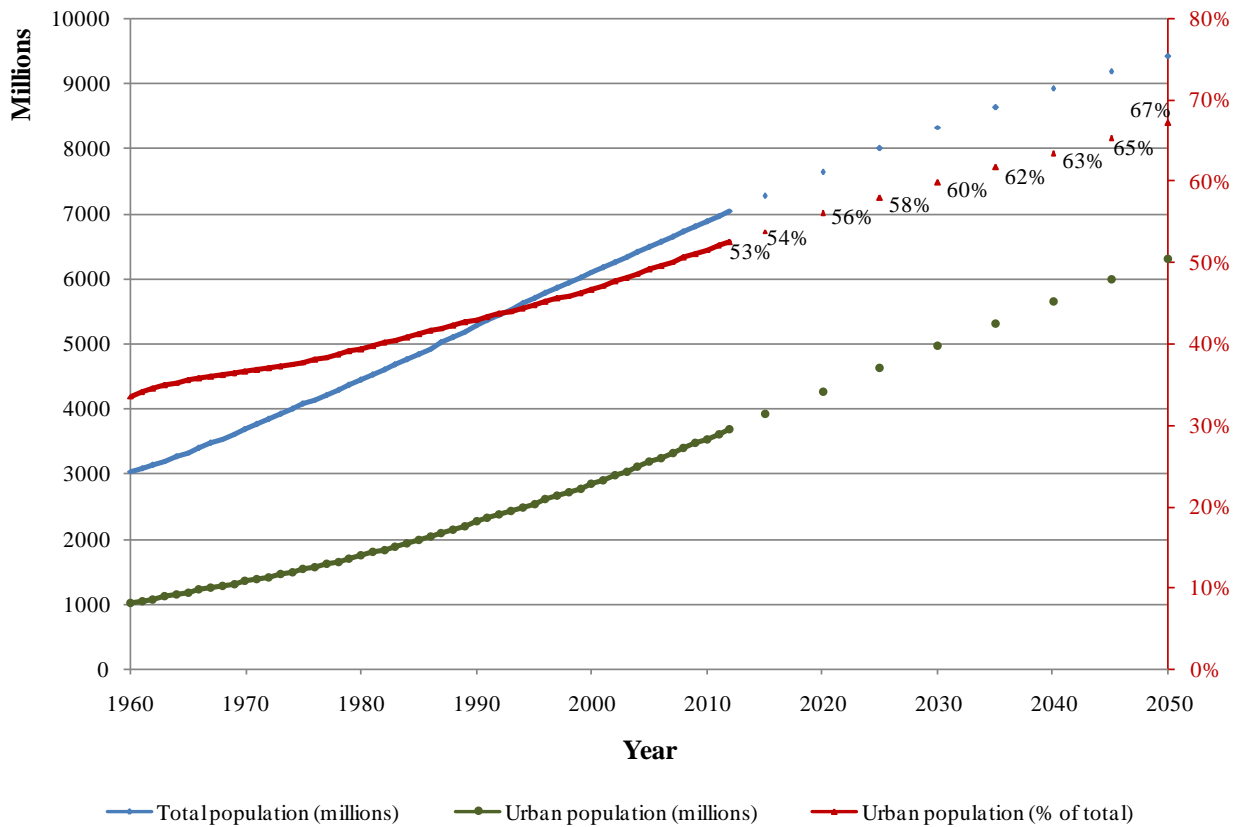


Fig. 1. Evolution of world population and urban population between 1960 and 2012 and forecasts 2050 (source: The World Bank)

Airplanes will be only used for long, cross- and intercontinental distances while high speed trains will be mainly used for long hauls. High speed subways and trains would be the main form of transportation used to get from one city to the next and from suburbs to downtown areas. Individual transport will be used mainly to cover the last few kilometers and happen only on a shared basis. Different layers of horizontal mobility will coexist at street level, underground and above street-level for pedestrians and there will be connections between them: mobility will become 3D.

On average, pedestrians do not like to walk more than 400 m, a range in which they will typically switch between modes of transportation. However, the average distance between metro stations in the city center is around 800 m to 1 km. There are some solutions capable to bringing passengers closer to conventional public transport like automated cabin based systems or PRT (Personal Rapid Transit) but they have low capacity so their use is limited in areas of high population density. To find a high capacity transport system suitable for distances between 200 m up to 1000 m could solve many challenges when configuring the cities of the future.

## 2. VARIABLE SPEED MOVING WALKS REQUIREMENTS

As part of present and future transportation trends and the need to fulfill increasing urban mobility requirements a gap in systems for transfer distances of between 200 and 1000 meters has been identified. Such trips are more demanded every day as urban mobility transportation needs and railway and airport sizes increase. For instance many airports use a several terminal facility structure so there is the need to commute between buildings typically 1000 m apart from each other. Other possible applications in this range are train and metro stations, transport interchangers, access from parking lots to exhibition centers, fairs or amusement parks.

Travel distances less than 200 m are normally covered by conventional moving walks, while distances higher than 2000 m are handled by APM (automatic people movers) (Fig. 2). For such distances travel time for conventional moving walks is too high as speed is usually limited for safety reasons. Cabin systems are not continuous, limiting achievable flow capacity, and requiring complex equipment, meaning higher financial and space resources. Also during breakdowns passengers are unable to complete the travel distance by their own means. As a result cabin systems are mostly used for long distance applications when their high speed effectively reduces travel time.

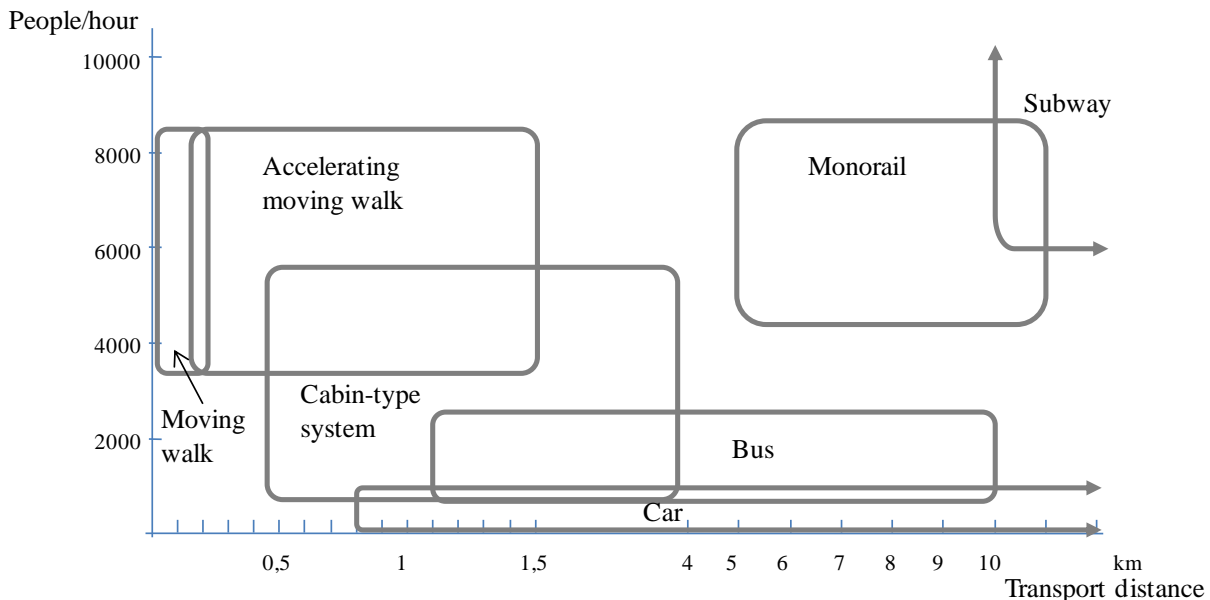


Fig. 2. Passenger flow and urban travel distance comparison of different people transportation systems (Source: internal research)

Variable speed moving walks are horizontal continuous transportation systems with the purpose of covering this identified gap in a continuous way and travel speeds around 3 to 4 times higher than conventional moving walks. Several moving walk manufacturers have tried to develop a system that can successfully give response to this need, but there are several technical challenges that need to be solved.

### 3. APPLICABLE STANDARDS

Variable speed moving walks have not been commercially available until mid 1990's and their application has been very limited. Subsequently, standards have not considered them specifically until very recently and yet there are very few references in current moving walk legislation. The main critical risk for passengers using a moving walk related to travel speed is the transition between the fixed part of the moving walk and the movable part if the relative speed is too high. Variable speed systems in which there is only one discrete speed change between fixed surface and maximum speed surface are considered safer in a similar way to conventional moving walks; given that the continuous speed increase occurs with a low acceleration value.

Regarding the most common applicable standards, "EN-115:2008+A1:2010 [1]" includes a brief reference to variable speed moving walks in chapter 5.4.1.2.3. Speed of conventional moving walks is limited typically to 0.75 m/s although speeds up to 0.9 m/s are accepted in some situations. However such limitations do not apply to moving walks with acceleration paths or with systems travelling at different speeds. "ASME A17.1-2010/CSA B44-10 [2]" standard also limits the maximum treadway speed for moving walks depending on the usable surface slope to 0.7 m/s or 0.9 m/s. The tenth edition of the Code (1981) incorporated Appendix G, Recommended Practice for Accelerating Moving Walks. This appendix was removed in subsequent editions so variable speed moving walks are not mentioned anymore.

Several studies identify the possibility of loss of balance depending on the acceleration. For instance, De Graaf, B. and Van Weperen, W [9] state that balance is maintained in a standing position with acceleration values lower than  $0.5 \text{ m/s}^2$ . Other studies recommend maximum jerk values of  $0.5$  to  $0.6 \text{ m/s}^3$  for public transportation systems. Standards already state safe maximum acceleration values. Accelerating moving walks using such values should be as safe as conventional moving walks regarding speed increase. ASME A17.1-2010/CSA B44-10 [2] allows an acceleration and deceleration rate of up to  $0.3 \text{ m/s}^2$  in conventional moving walks start-up. EN-115:2008+A1:2010 [1] allows acceleration rates up to  $0.5 \text{ m/s}^2$ .

Variable speed systems usually are based on a modification of the usable surface of the pallet and handrail. Any usable surface modification should be addressed regarding safety. The use of slotted surfaces and combs is usually considered the safest configuration in a similar way to the entry and exit areas of conventional moving walks. Ergonomic studies are carried out to increase passenger comfort and avoid any possible uncomfortable perception due to the higher speed compared to conventional moving walks.

Specifically for European legislation the harmonized standard identifies all potential safety risks according to EN ISO 14121-1:2007 [3]. Fulfilling such standard is a condition which assures the assessment of all identified machinery risks applied to moving walks. As some new risks may appear due to the specific characteristics of variable speed moving walks an individual risk assessment according to ISO 14798:2009 [4] is needed.

Due to the acceleration and higher speed values, the impact of passenger whole body vibration taking into account comfort but also health, motion sickness and perception in all three directions is filtered and evaluated according to ISO 2631-1:1997 [5], ISO 18738-2:2012 [6] and ISO 8041:2005 [7]. As a general rule pallet vibration values lower than  $0.315 \text{ m/s}^2$  are considered not uncomfortable. Regarding hand vibration, standard ISO 5349-1 2001 [8] establishes the general rules to evaluate health impact due to vibrations on hand but there is no specific assessment regarding comfort. Noise values should also be evaluated according to ISO 18738-2:2012 [6]. EN-115:2008+A1:2010 [1] does not consider noise as a significant nor relevant hazard while emission sound pressure level is expected not to exceed  $70 \text{ dB(A)}$  for conventional moving walks.

#### **4. STATE OF THE ART**

First attempt to have a variable speed people transportation system was developed at the end of 19<sup>th</sup> century and finally constructed to start operation during the 1900 Paris Universal Exposition (Figure 3). The concept was based on two parallel conveyors running at different speeds and located adjacent to the fixed floor so that the passenger could move laterally from the slow speed surface to the high speed surface. The unit ran for a few months and several minor accidents were registered. The machine was finally closed and no attempt was made to improve the system.

At the end of the 1960's, G. Bouladon and P. Zuppiger patented a new concept for a variable speed transportation system (US3580182) [10] (Fig. 4). It was based on moving platforms with rhomboid shapes which move laterally in a certain relative position to the boarding and landing areas. The result was an "S" shaped moving walkway which had wide areas in the slow speed sections and narrow ones in the high speed sections.

Based on the concept from G. Bouladon and P. Zuppiger, Dunlop initially and Mitsubishi some years later, developed driving systems resulting in real prototypes. The main disadvantages of this concept were the high space required for installation, the complexity of the driving systems and the difficulties to find a variable speed handrail synchronized with the moving platforms.

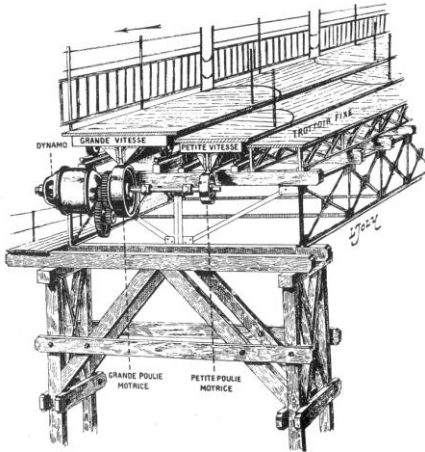


Fig. 3. L.Joly, Illustration, 1900 Paris Universal Exposition two speed moving walk diagram [15]

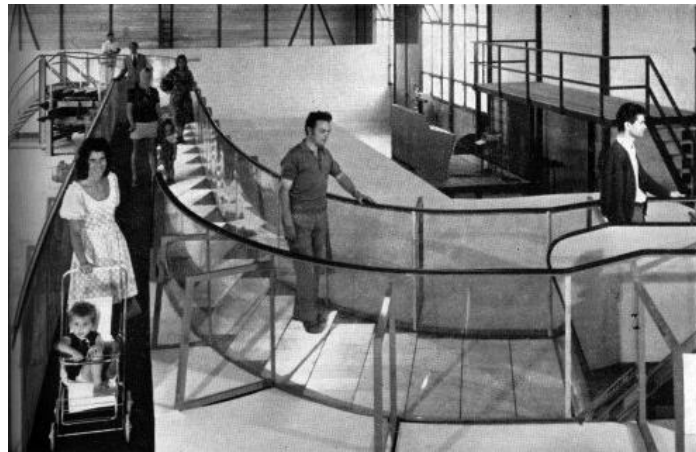


Fig. 4. G. Bouladon and P. Zuppiger variable speed moving walk using rhomboid platforms

Based on an invention from the Loderway company (J.L. Loder - EP0352968) [11] a variable speed transportation system unit was installed in Brisbane airport during the 1990's. The working principle consisted on a succession of closed belts running at different constant speeds. In parallel to the running belt, several running handrails synchronized with the moving floor, giving the user an area to hold the handrail. The main disadvantage of this type of conveyor is the speed leap between the different belts running at different speeds. Loderway moving walkway was opened to public for some months showing the feasibility of variable speed conveyors.

Up to date, the most ambitious attempt to install a commercial variable speed conveyor was carried out by the company CNIM [14] at Montparnasse metro station in Paris. The concept (Fig. 5) was based on closed treaded belts running in constant speed areas while the acceleration between them is achieved by a succession of small rollers running at different speeds. Transition between the acceleration and constant speed areas is achieved by means of free rotating elements covering the total surface of the transition. CNIM also implemented the first variable speed solution for the handrail. The concept was based in a rigid moving area and a flexible one acted by a mechanism with a guiding system which changed its length accordingly to achieve the required kinematics' behavior. Due to some accidents registered, most of them located in the variable speed transitions, the units were closed to public after some months of operation.

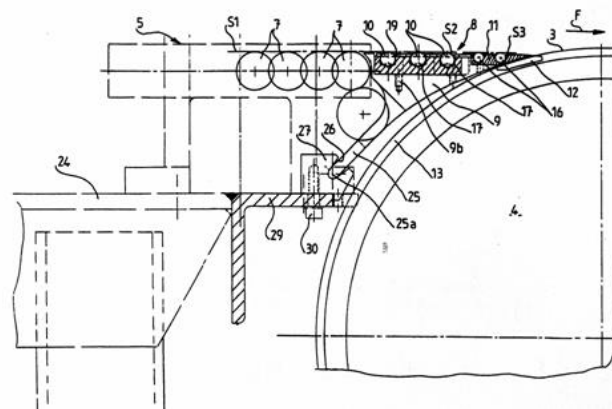


Fig. 5. CNIM variable speed system detail [14]

Hitachi patented another concept of variable speed conveyor based on a retractile pallet which is completely folded in the low speed section while a treaded surface is exposed to the users between adjacent pallets as the speed increases. Maximum speed of this concept is limited to 1.8 times

boarding speed, which is below the potential speed increase of the other variable speed concept systems. In addition, in the invention (GB 2264686) [12] it is not mentioned how a smooth transition between the treaded surface and the rest of the areas is achieved when the treaded surface disappears in the area where the speed is reduced.

## 5. ARCHITECTURE OF THYSSENKRUPP VARIABLE SPEED MOVING WALK

Currently there are only two variable speed moving walk units in operation in a public environment, which have been developed by ThyssenKrupp and commercially named as TurboTrack<sup>®</sup>. The first related patent was published in 2003 (M. Alemany et al. - EP1253101) [13]. Since then several more patents were published describing the different subsystems of the overall conveyor and several possible solutions proposed. The transportation system is based on a principle of a succession of overlapped pallets (Fig. 6) which form the moving surface. Each pallet consists of a short body pallet and a long body pallet with a hinge joining them. In the high speed area, both the short and long pallets are accessible to passengers while as the speed is reduced long pallets start to move underneath the adjacent short pallet. When the conveyor reaches the minimum speed, long pallets are not accessible to passengers and the usable surface is formed only by the succession of short pallets.

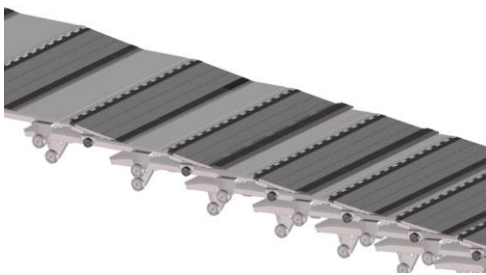


Fig. 6. ThyssenKrupp TurboTrack pallet system



Fig. 7. Grasps and covers distribution of the handrail system

During acceleration and deceleration, there is a relative movement between the short and the long pallets. Combs are located in the short pallets to mesh into the adjacent long pallet and assure a smooth transition for the users in case they stand in the long pallet in the deceleration area. This pallet concept is a continuous and variable transportation system that has been safely working at Pearson Toronto airport since April 2009.

From a user point of view, the TurboTrack handrail system is similar to the pallet. The moving area consists of a succession of two parts, grasps and covers (Fig. 7). In the low speed sections only grasps are accessible to the user while as the moving walk accelerates covers appear below between adjacent grasps. Small treads in the grasp intermeshing into the cover reduce the potential risk of entrapments between both components due to relative movement.

In the high speed areas, the pallets are moved by a chain drive system (Figure 8). When the pallets reach the variable speed area, they are mechanically disengaged from the chain and engaged to a variable pitch screw located longitudinally to the conveyor. As the pitch of the screw decreases the speed of the pallet assembly is reduced proportionally. When the pallets reach the comb level at low speed, the pallet speed is increased again by changing the pitch of the screw and is mechanically engaged to the chain when it matches the chain constant speed. With this system a continuous speed profile is achieved between the boarding low speed areas and the central high speed areas (Fig. 10)



For driving the handrail (Figure 9) the cover is connected directly to the drive chain and it is running all along the moving walk at high speed. In the high speed areas the grasp is mechanically engaged to the drive chain and moved by it. When the grasp reaches the variable speed area it is mechanically disengaged from the chain and driven by a variable pitch screw synchronizing the grasp with the short pallet below. The power to move the handrail drive is transmitted from the main drive shaft with a chain.

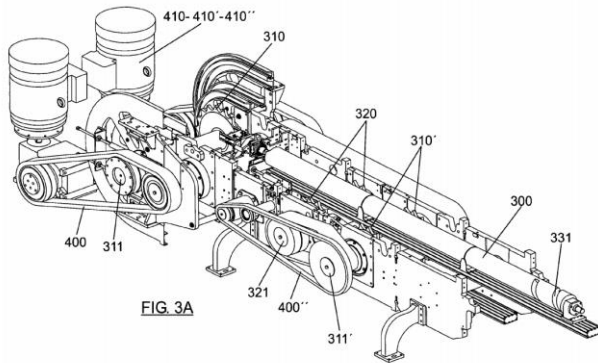


Fig. 8. Pallet band drive and transmission systems

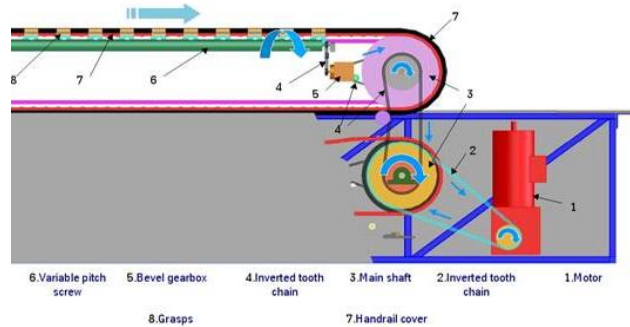


Fig. 9. Handrail drive and transmission

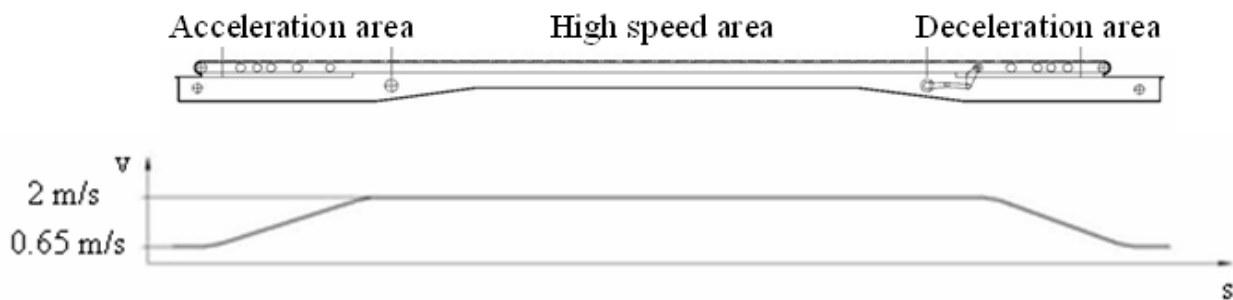


Fig. 10. Variable speed moving walk speed profile, speed (v) vs. distance (s)

The synchronization of the different drive systems of the moving walk is carried out completely mechanically by means of gears, wheels and chains. The application of alternative technologies like linear motors to electronically control the variable speed and drive any of the TurboTrack subsystems could potential simplify the architecture of the system.

## 6. APPLICATION OF LINEAR INDUCTION MOTOR TECHNOLOGY IN VARIABLE-SPEED SYSTEMS

Up to now all variable speed moving walk systems have used centralized drives to achieve pallet band movement. However it would be possible to drive pallets individually provided that the required speed profile is achieved independently. The most effective way is to drive pallets linearly in the direction of motion but there is a challenge on how to provide such power to each pallet. This may be possible using Linear Induction Motor (LIM) technology.

A linear motor is an electric motor with its stator and rotor distributed so that instead of rotating produces a linear force along its length. The applied force is linearly proportional to the electric current and the magnetic field (Lorentz-type actuator) (Eq.1)

$$\vec{F} = q * \vec{v} \times \vec{B} \quad (\text{Eq. 1})$$

where  $\vec{F}$  is the applied force,  $q$  is charge of the particle,  $\vec{v}$  is the velocity and  $\vec{B}$  the magnetic field,

Linear synchronous motors (LSM) are linear induction motors with a three phase winding on one side of the air-gap and a set of magnets with alternating poles on the other side. These magnets might be permanent or electromagnets. The operating principle of the linear motor allows obtaining an energy conversion form with clear advantages for translation purposes as the linear motor provides propulsion force with only electromagnetic link between the fixed and mobile parts without the need of any additional mechanical transmission from rotational movement.

In rotational motors a fixed distance between inductor and inductive (rotor and stator) parts is easily achieved as the movement uses always the same reference. One challenge when working with linear motors for horizontal motion is to maintain the gap when the moving part is changing its position. To control this gap it is critical to have low values of the inducted magnetic field.

Two types of linear motors exist depending on the nature of the armature: iron-core and iron-less. In iron core (Fig. 11) motors there is a unidirectional non-compensated force between the inductor and the inductive. This force is variable and depends more on the nature of the armature rather than on the air gap. In order to avoid excessive friction a robust guiding system is then required. The magnetic attraction is weaker with mixed induced because the magnetic gap will be greater than in other types of armature, as it comprises the thickness of the conductive plate. It must be considered that this magnetic attraction is harmful for the application to moving walks, even as iron-core linear motors are typically cheaper.

With a strictly symmetrical system and a configuration with two inductors, one at each side of the inductive, or with two inductives, one at each side of the inductor, the attraction forces are compensated. The differential force will be weaker than the unidirectional attraction.

For iron-less motors the inductive is made of isotropic non-magnetic conductor material like copper or aluminum. The configuration of the motor can be with two inductors or one inductor and a yoke closing the flow. Because the design is balanced and the coil section contains no magnetic material the motor has no attraction force and there is absolutely no cogging. The only force generated is the thrust force. Due to the high magnetic resistance the coil inductance is relatively low allowing high change rates for very fast movements and reactions to the disturbing forces. These features provide very short reaction times and high speed to this highly dynamic motor which will require accurate control by means of a fast and a precise controller and amplifier. One disadvantage of this type of motor arises from the fact that it is necessary to have two rows of magnets within the sandwich therefore increasing the cost of the magnet yokes.

This type of motor is the most adequate one to drive pallets in order to achieve variable speed. The magnet yoke which does not require power is the one installed in the moving part (the pallet) while the motor windings are the path through which the magnet yoke will run.

One requirement is that only one pallet can coexist in the same motor as it is not possible to have different control through one motor. Motors must be as close as possible, even side by side, so there is not transition between them, although due to the expansion effect a small gap is needed. This is crucial in the acceleration and deceleration areas where high accuracy is required as it is necessary to react as fast as possible to any change in the pallet load. In order to reduce the number of motors, in the central area they are grouped together leaving gaps between groups.

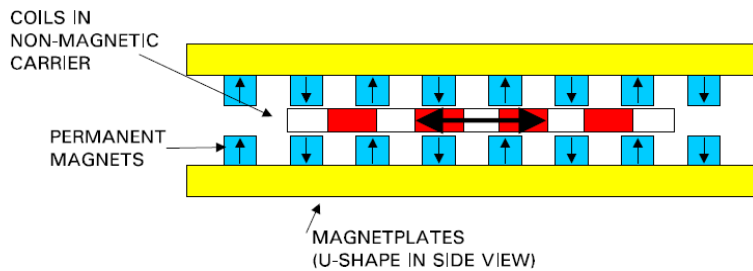


Fig. 11. Iron core motor schematic [16]

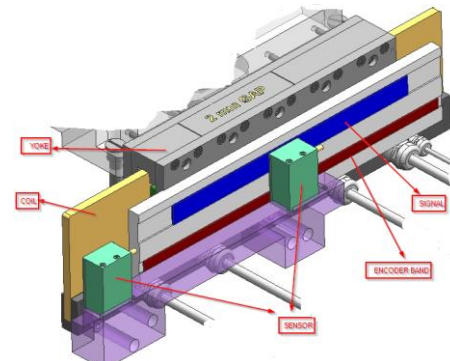


Fig. 12. Location of the encoder and sensor

Linear applications require a sophisticated motor position and velocity feedback. To achieve accurate control of the motors it is necessary to have a position sensor (Fig. 12). A linear encoder and a servo controller are used in the positioning system. The ideal solution would be to have an absolute encoder so the location of each pallet is known at anytime. This requires having a measuring device in the floor and a reading sensor in each pallet; since this solution requires the wiring of moving parts, the solution must be reversed. The problem then is how to build a continuous measuring device. To solve this, a double sensor solution is considered: the incremental encoder signal indicates the position and an additional signal indicates when the magnet yoke enters the motor. A single sensor developed for this application provides encoder pulses only when a magnet yoke is detected. Sensors are placed every short distance in the area of acceleration and deceleration while in the central area a small group of sensors can cover longer distances.

To handle synchronization of all drives in real time a master computer is used. The main feature of the system is that every single motor performs exactly the same specific movement depending on the position and speed. This allows splitting the complete kinematics of the moving walks in small portions and each portion is assigned to one motor which can work mainly autonomously as the information is stored. The control system (Fig. 13) is then more decentralized and as a result simpler. Only a central master is required to synchronize the clock of each motor with a fast execution cycle. To assess the feasibility of the linear motor configuration maximum needed motor force are defined by considering different load scenarios, distributing passengers along the moving walk areas.

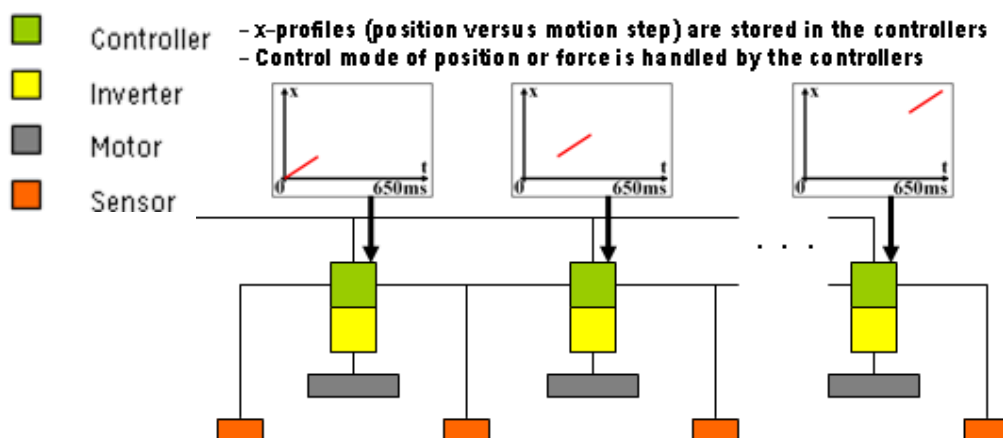


Fig. 13. Decentralized control system scheme

## 7. CONCLUSIONS

Variable speed moving walks are identified as a possible sustainable and accessible solution to present and future transportation needs in urban environments as city population increases and mobility becomes more complex. Travel distances from 200 m to 1000 m may be covered continuously with higher capacity, low commuting time and reduced costs. Continuous acceleration systems are safer than discrete speed increase systems, provided that acceleration values are low.

Many technical challenges need to be solved to achieve variable speed in moving walks and some manufacturers have developed different concepts during the past years.

Currently two units of Thyssenkrupp variable speed moving walk TurboTrack<sup>R</sup> are installed and in operation. The continuous acceleration speed profile system is based on a two-body pallet design mechanically driven by gears, chains, rollers and variable pitch. The application of alternative technologies like linear motors to drive and electronically control the variable speed is identified to potentially simplify the architecture of the system.

Linear synchronous motors have a three phase winding on one side of the air-gap and a set of permanents or electromagnets with alternating poles on the other side and can drive pallets individually to achieve the needed speed profile, as force can be applied directly in the direction of travel. Air gap control is critical to have low values of the inducted magnetic field.

For iron core motors there is a non-compensated force while iron-less motors are made of isotropic non-magnetic conductor materials and have no attraction force and there is no cogging. This type of motor is the most adequate one to drive variable speed pallets. The magnet yoke is installed in the moving part while the motor windings are the path through which the magnet yoke will run. A double position sensor is used for accurate motor control position and velocity feedback for the overall position and when the magnet yoke enters the motor. A master computer is used for synchronization of all drives in real time, as every motor performs the same movement depending on its position and speed mainly autonomous as the information is stored.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## The Application of Simulation to Traffic Design and Dispatcher Testing

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**Abstract.** Simulation is a popular traffic design tool, but there are many different ways in which it can be applied and the interpretation of results can be difficult. The relationship between round trip time calculations and simulation is explored, demonstrating consistency, but also highlighting why results can be very different. Simulation templates allow hypothetical and measured traffic patterns to be applied in the selection of lifts for new buildings, and in assessing the benefits of modernisation. The strengths and weaknesses of popular templates are discussed. Common misunderstandings are explained. Dispatcher testing can be approached in a similar way to traffic design, but success in sample traffic design simulations does not guarantee consistent performance across a range of traffic conditions and building configurations. A more comprehensive approach is proposed.

### 1. INTRODUCTION

Lift simulation models of varying sophistication have been written and applied since the early 1970s [1]. The continuing improvements in computer technology and software development tools make increasing complex and comprehensive simulation models feasible. In the late 1990s non-proprietary simulation software for modern operating system became available, making simulation popular and available to most lift companies and consultants. Lift simulation is a very powerful tool. However it is good practice to start all design exercises with a round trip time calculation [2].

With round trip calculations a single, average round trip is modelled. In simulation the whole process of passengers arriving at the landings, registering their landing calls, boarding the lifts when they arrive, registering their car calls and then alighting at their destination is modelled. Simulation calculates the performance for every call and every passenger.

Simulation can be used to model scenarios that cannot normally be analysed with the round trip time calculations, including:

- i. Light (non-peak) traffic
- ii. Changing levels of traffic, e.g. the increasing levels of traffic as the work start time approaches in an office building
- iii. Mixed types of traffic, e.g. goods and passenger traffic using the same lifts
- iv. Lifts in the same group with different speeds and sizes.

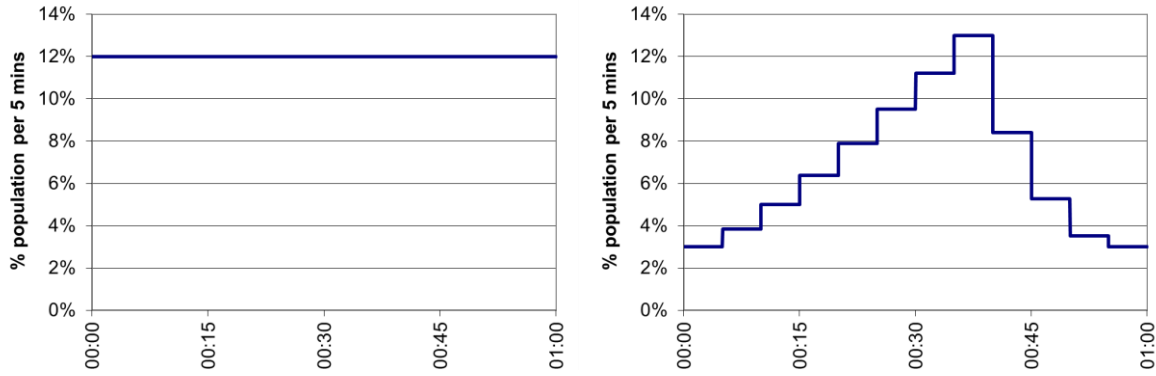
### 2. DESCRIBING TRAFFIC

With general analysis round trip calculations [3] the following may be analysed:

- i. mixed traffic, defining a demand as a percentage of the building population, divided into incoming, outgoing and interfloor components
- ii. entrance level bias to allow for car parking floors, restaurant floors and other utility floors

- iii. arrival rate and destination probability tables, for traffic which cannot be described in simpler terms.

All these ways of describing traffic can all be applied in simulation. With round trip time calculations the assumption is that demand is constant; with simulation templates introducing a time element can be considered, see Figure 1. This paper considers constant and step templates; these are theoretical templates not based on real traffic in buildings. Finally templates derived from traffic surveys will be considered.



**Figure 1 Demand may be constant or vary with time**

### 3. CONSTANT TRAFFIC TEMPLATE

With a constant traffic template the premise is that if a system has a handling capacity of x%, it can sustain that demand indefinitely. This is directly analogous with the round trip time calculation.

#### Example 1 Simulation of up peak calculation

Perform a round trip time calculation and simulation for the parameters given in Table 1. Note that dwell times are included in the round trip time calculation. Run the simulation for 30 minutes ignoring the first and last five minutes to allow for start and end conditions. Apply a group collective algorithm with up-peak mode.

**Table 1 Up peak calculation and simulation parameters**

Rated speed	2.5 m/s	Passenger loading time per person	1.2 s
Acceleration	0.8 m/s <sup>2</sup>	Passenger unloading time per person	1.2 s
Jerk	1.6 m/s <sup>3</sup>	Number of floors above main entrance	14
Allowance for motor start delay	0.5 s	Total height of un-served floors in express zone	0 m
Levelling delay (s)	0 s	Floor heights (m)	Ground to Level 1, 5.0 m; other floors 3.8m
Number of lifts	5	Floor populations	48 for all floors
Lift capacity	1000 kg	Passenger mass	75 kg
Car area	2.4 m <sup>2</sup>	Area per person	0.21 m <sup>2</sup>
Advanced door opening time	0 s	Capacity factor by area	80 %
Door opening time	1.8 s	Capacity factor by mass	80 %
Door dwell time	2 s	Round trip time losses	5%
Door closing time	2.9 s		

Results are given in Table 2; in this case there is a close correlation between the up-peak calculation and simulation.

**Table 2 Result for comparison between round trip times and simulation**

	<i>up-peak calculation</i>	<i>simulation</i>
Average up-peak interval	33.3 s (result)	33.3 s (result)
Percentage population served in up-peak five minutes	14 % (result)	14% (input)
Average no of passenger in car	10.4	Not calculated
Average waiting time	Not calculated	20.6 s

**Example 2 Simulation demonstrating saturation**

A lift group saturates when the demand exceeds the handling capacity. As the lifts cannot cope with the traffic, the longer the simulation runs, the longer the passenger waiting times become. Increasing queue lengths develop as the simulation progresses.

To demonstrate saturation, repeat the simulation in Example 1 with the demand increased from 14% to 15% and then to 16% of the building population requiring transportation in five minutes. Results are given in Table 3.

**Table 3 Result for comparison between round trip times and simulation**

Percentage population served in up-peak five minutes	14 %	15%	16%
Average waiting time	20.6 s	38.9 s	85.8 s
Average up-peak interval	33.3 s	33.8 s	34.3

Notice that with increasing demand the interval remains relatively stable. Up-peak interval is the time between lift departures from the entrance floor. For all three results the lifts are departing full from the ground floor. When the demand increases, a queue is forms. So, passengers have to wait more than one interval before they can board a lift. This is reflected in the rapidly increasing average waiting times and queue length.

**Avoiding confusing simulation results with the constant traffic template**

Round trip time calculations for office buildings are often carried out to establish the maximum handling capacity of a system. So, if a simulation is run based on a round trip time calculation it is likely that the simulation will be near or at the saturation point. If the simulation saturates, then results become unstable; a solution which was acceptable when analysed with a round trip time with simulation can present long queues and unacceptable waiting times. As the simulation is unstable, small changes in any parameter can have a large and sometimes counter-intuitive effect on results.

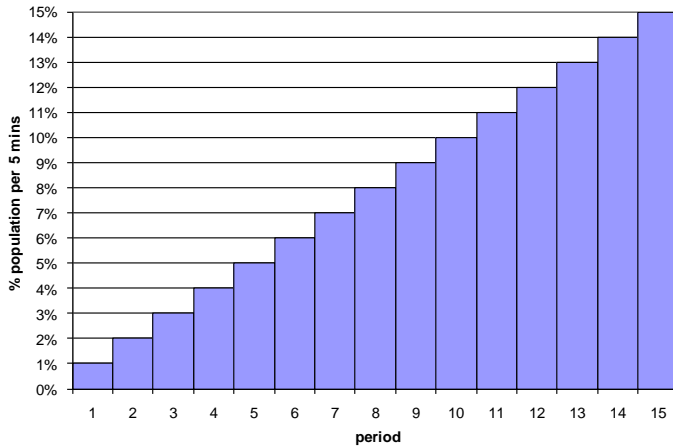
When comparing round trip time calculations with simulations, it is important to note:

- i. often designers using round trip time calculation do not consider door dwell times
- ii. round trip time calculations are based on averages and may be based on the assumption a car is loaded with say 9.9 persons; a simulation with multiple runs also yields an average, but in each simulation the maximum car load is an integer number of persons
- iii. unless a round trip time inefficiency is used, round trip time calculations assume an ideal system with, for example, no bunching, no door re-openings or other “real life” delays.



#### 4. THE STEP PROFILE

This template shown in Figure 2 starts with a low demand and increases constantly or, in increments of 1% every period. The demand can be pure up-peak, or any combination of mixed traffic. The premise of this approach is that the system’s performance is tested across a range of traffic intensities.



**Figure 2 Passenger demand for step profile increasing by 1% every period**

This presentation is useful as it highlights to the customer that the waiting time, loading, and other parameters are dependent on demand. A system that manages 12% of the design population in 5 minutes may be sufficient in most buildings. However, if it can transport a greater demand without saturating, it is more likely to manage, for example, if the building population exceeds the design population. The simulation should continue to at least 1% beyond the design value for passenger demand.

#### Example 3 Application of step profile

Repeat Example 2 with a step profile. Begin at 1% demand increasing traffic at 1% increments every 30 minutes up to a maximum of 16%. Results are given in Table 4.

**Table 4 Quality of service results for increasing demand**

<i>Demand (% population per five minutes)</i>	<i>Average Waiting Time (s)</i>	<i>Average Transit Time (s)</i>	<i>Average Time to Destination (s)</i>
1	0.0	25.9	26.0
2	0.1	29.8	29.9
3	0.1	31.4	31.4
4	0.1	33.8	33.9
5	0.5	37.8	38.3
6	0.7	43.4	44.2
7	1.2	48.5	49.7
8	1.8	53.2	55.0
9	2.7	57.6	60.3
10	4.1	64.1	68.2
11	4.8	67.9	72.8
12	9.7	72.4	82.1
13	12.6	75.3	88.0
14	21.6	79.1	100.8
15	83.4	80.1	163.5
16	183.2	67.3	250.5

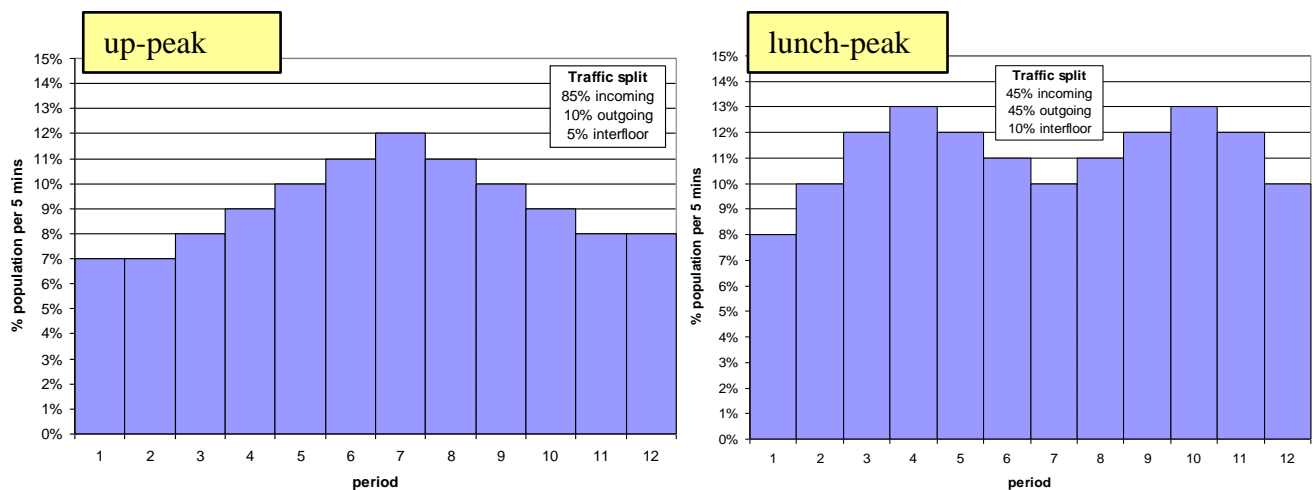
When the demand exceeds the handling capacity (15%), the system becomes unstable. Up to this point the table provides a good indicator of how the system will perform across a range of traffic intensities. Note in the close correlation between the waiting times calculated with the constant traffic template and the step profile when the demand is 14%, see Table 5.

**Table 5 Comparison of constant traffic template and step profile template.**

	<i>Constant traffic template</i>	<i>Step profile template</i>
Average waiting time at 14% up peak demand	20.6 s	21.6 s

## 5. SIMULATION TEMPLATES DERIVED FROM TRAFFIC SURVEY

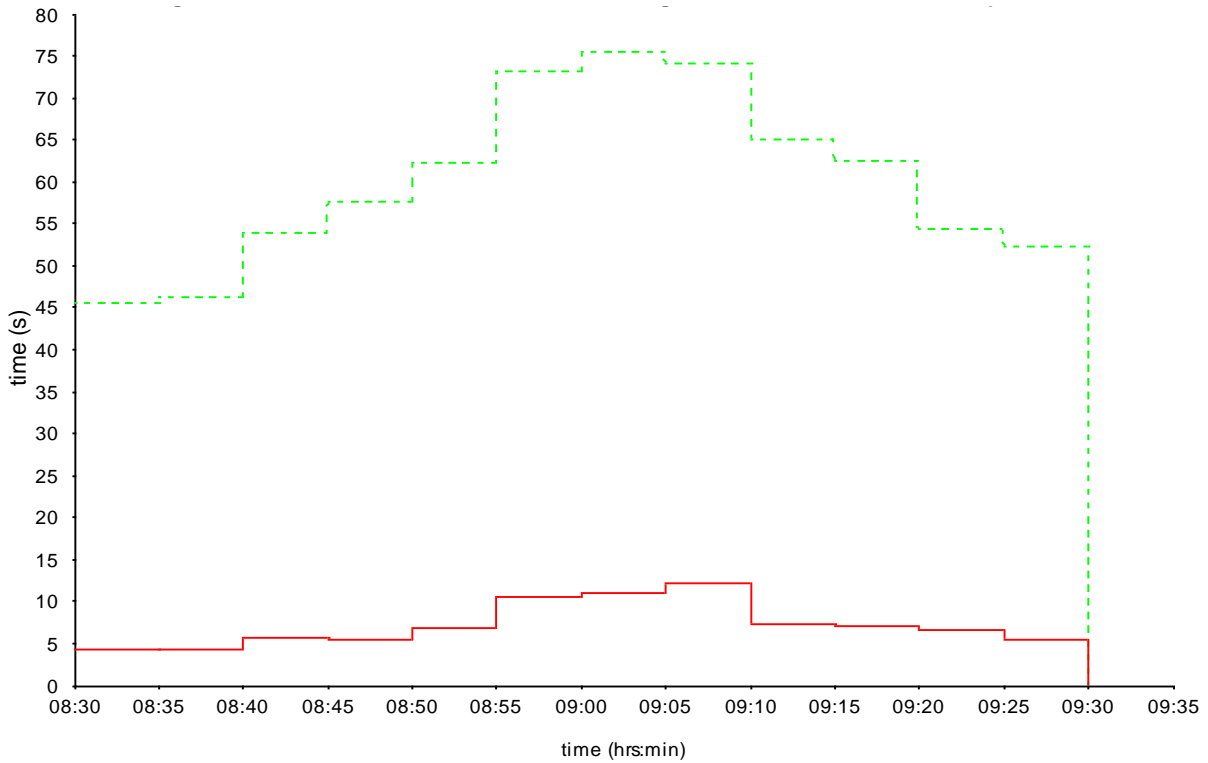
The templates presented in previous sections are not intended to represent actual passenger demand in buildings; they are tools to assist designers establish an appropriate design. The most authoritative position when predicting how a proposed lift installation will perform is to design applying evidence based research. Templates have been proposed which are intended to represent real traffic in actual buildings [4], [5], [1]. New design templates for offices were developed [2] to reflect the traffic in modern office buildings, see Figure 3. Each template represents one hour in twelve 5-minute periods.



**Figure 3 CIBSE modern office up-peak and lunch-peak traffic templates**

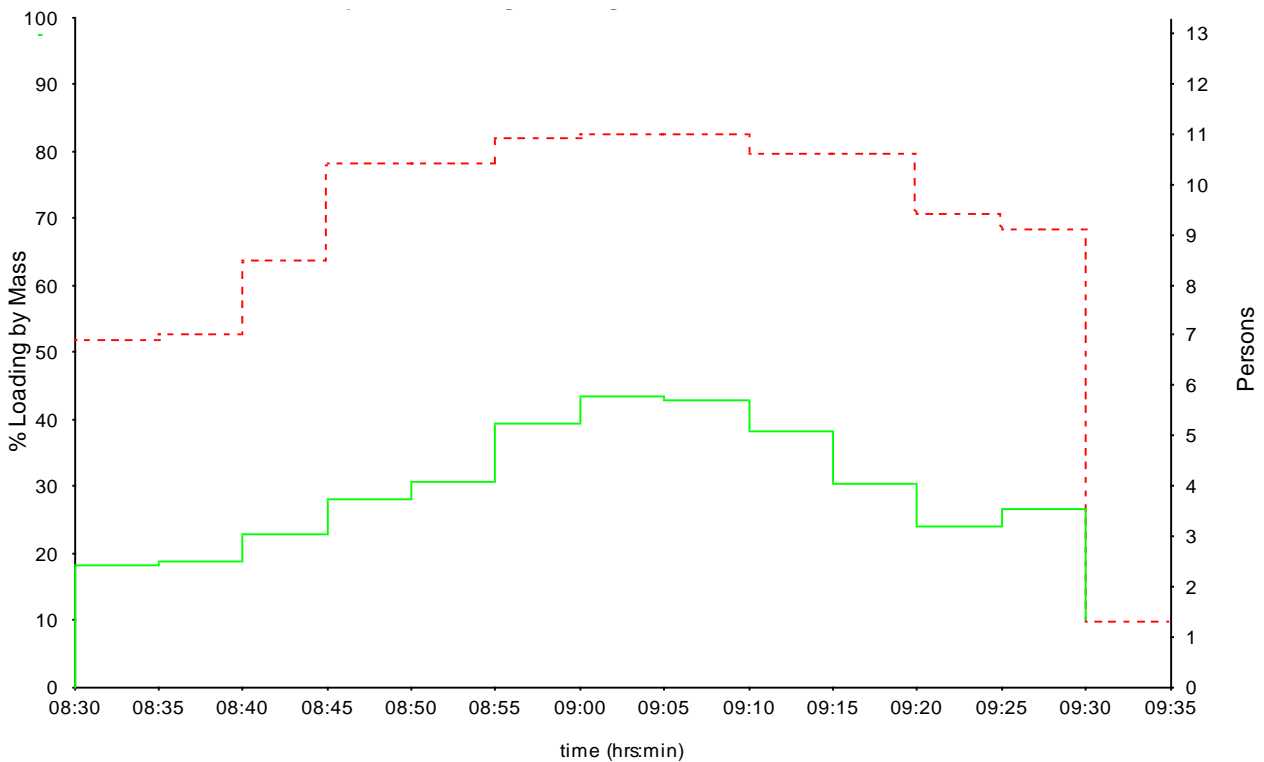
### Example 4 Application of modern office templates

Repeat Example 1 in simulation applying the CIBSE modern office templates. Results for simulations based on the up-peak template are given in Figure 4 and Figure 5. Test against target requirements for prestigious city office [2]. The up-peak requirements are for average waiting time during the worst five minutes not to exceed 20 seconds; and for the average transit time not to exceed 80 seconds. These requirements are both met.



Worst Average Waiting Time during any 5 min period (s) 12.1  
 Worst Average Transit Time during any 5 min period (s) 64.5

**Figure 4 Average waiting time (solid) and time to destination (dotted) applying CIBSE modern office up-peak template**

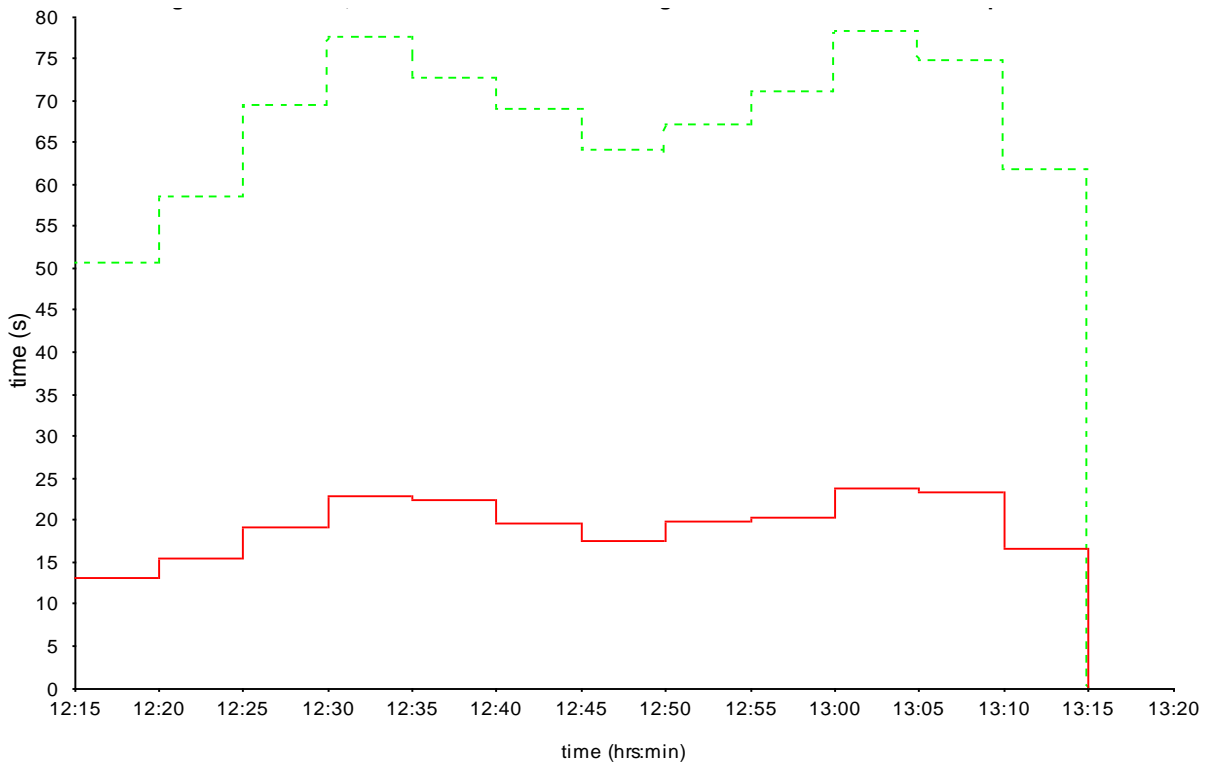


Worst Average Capacity Factor by Area during any 5 min period (%) 50.5

**Figure 5 Average (solid) and maximum (dotted) car loading on departure from home floor applying CIBSE modern office up-peak template**

The up-peak loading requirements are for the capacity factor by area not to exceed 80%. This is met.

Results for the simulations based on the lunch-peak template are given in Figure 6.



Worst Average Waiting Time during any 5 min period (s) 23.7  
Worst Average Transit Time during any 5 min period (s) 54.8

**Figure 6 Average waiting time (solid) and time to destination (dotted) applying CIBSE modern office lunch-peak template**

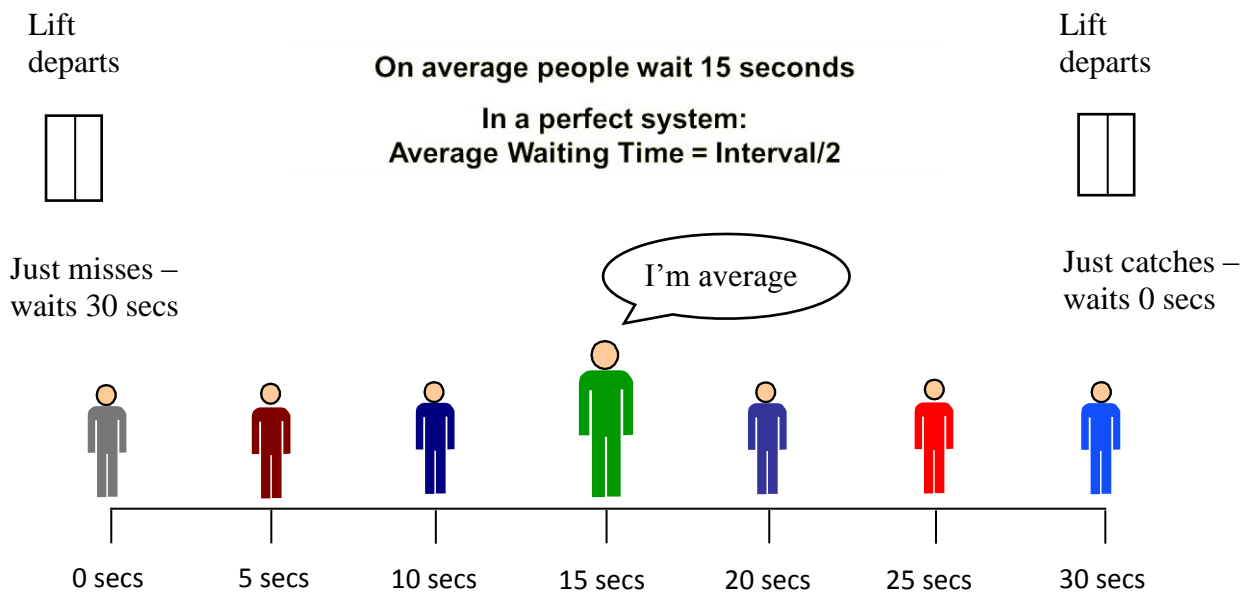
The lunch-peak requirements are for average waiting time during the worst five minutes not to exceed 30 seconds; and for the average transit time not to exceed 100 seconds. These requirements are both met. The lunch-peak loading requirements are for the capacity factor by area not to exceed 80%. This is met easily; loading during lunch is less critical as people are not all in the car at the same time; some in the car for the up trip, others for the down trip. Waiting times are typically longer as lifts stop for calls during both the up and down trips.

## 6. INTERVAL AND WAITING TIME

When clients and designers familiar with round trip time calculations first apply simulation, they sometime continue to use interval as a quality of service measure. This sometimes leads to confusion as interval does not always reflect quality of service.

### Interval in an ideal system

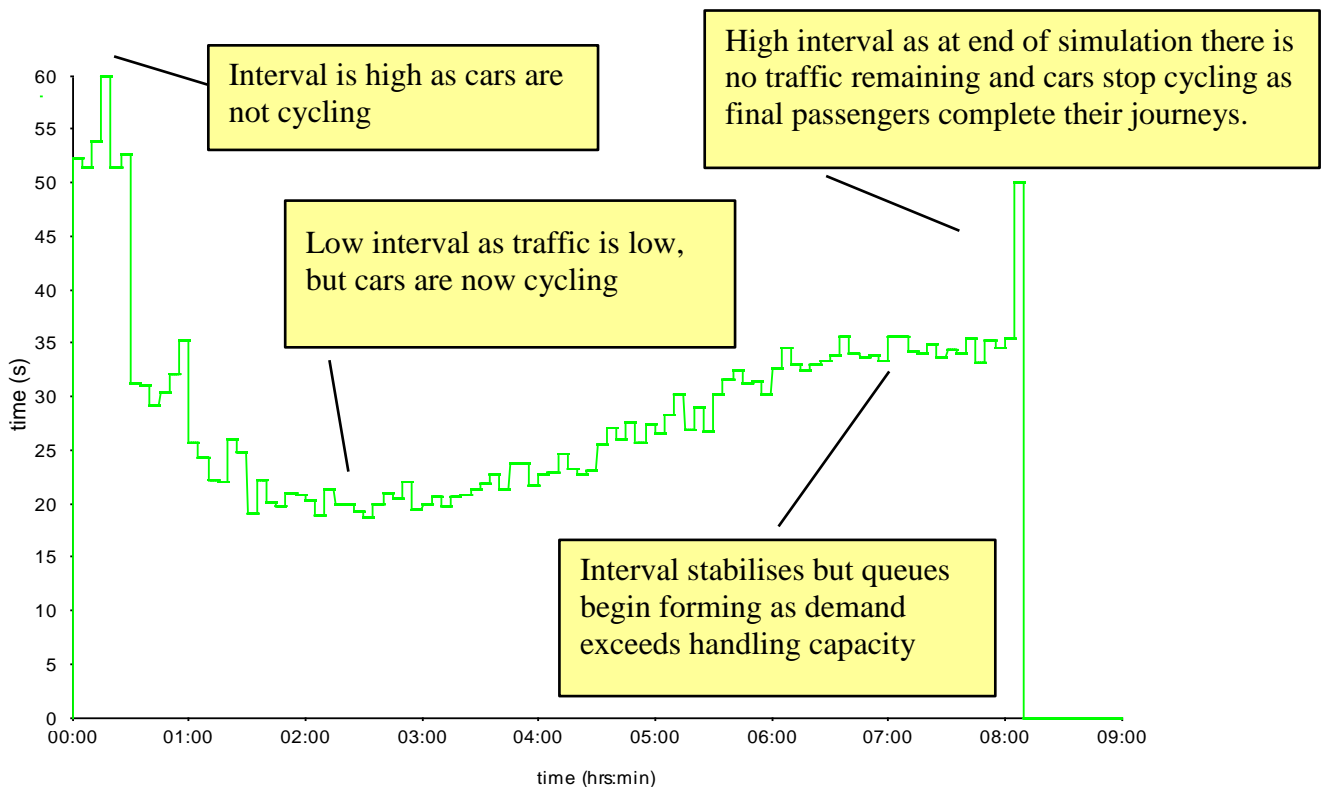
Consider a lift system with an interval of 30 seconds. A lift departs the main entrance floor every 30 seconds as indicated in Figure 7. If people are arriving at a constant rate, the first passenger shown on the time line just misses the lift. He or she has to wait 30 seconds. The final passenger shown on the time line just catches the lift, so waits 0 seconds. The average passengers wait 15 seconds. So, in a perfect system the average waiting time is 15 seconds, or half the interval.



**Figure 7 Comparing interval and waiting time**

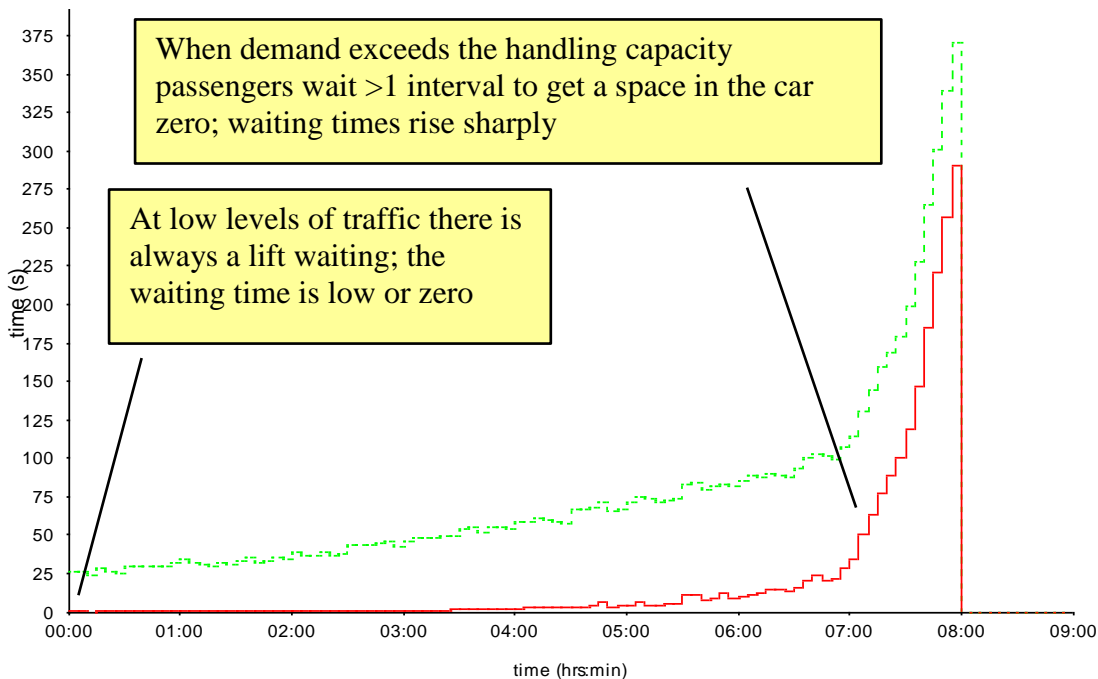
**Interval across a range of traffic intensities**

The scenario characterised in Figure 7 reflects our understanding of round trip time calculations. In the real world, and with more sophisticated simulation models, the relationship is not this simple. One way of investigating this is with a step profile. In Example 3 the up-peak demand increased by 1% every 30 minutes. Figure 8 shows the corresponding interval with increasing traffic demand.



**Figure 8 Interval for increasing traffic demand**

For the same demand profile, consider the plot of waiting time (and time to destination) as given in Figure 9.



**Figure 9 Average waiting time (solid) and time to destination (dotted) for increasing traffic demand**

The idealised interval to waiting time relationship seen in Figure 7 only occurs just before the simulation saturates. Average waiting time proves the better measure of quality of service.

### Other difficulties with interval

*Non-peak traffic* With low demand, the interval in simulation becomes high as cars are not being dispatched regularly from the main entrance floor; sometimes they are sitting idle, see the start of Figure 8. It is generally accepted [6] that for low traffic scenarios such as residential buildings, simulation is the better tool, and waiting time should be used in preference to interval.

*Multiple entrance floors* Interval is a measure of the time between lift departures from the main entrance floor. With multiple entrance floors, not every lift stops at the main entrance floor on every round trip. This causes high intervals; again interval falls down as a measure of quality of service.

*Destination Control* With destination control passengers are allocated to a specific car, so they do not take the next car to depart. So, even if the interval is 20 seconds, it may be two or three intervals until the car allocated to a passenger departs. Some early presentations of destination control reported excellent intervals, which were potentially misleading; the interval does not correlate with quality of service with these systems.

### Discussion

Interval is a very useful measure of quality of service in the context of round trip time calculations. In simulation it is an interesting result, but can be confusing without a clear understanding of what is being measured. If simulation is required, but the design criteria specified is interval, it is advisable to target an equivalent average waiting time. Barney suggests that the relationship is a function of loading [1], as also demonstrated in this paper. Strakosch [5] suggests the relationship is approximately 60%, which is consistent with the author's simulations at traffic levels marginally

below the saturation point. Therefore, for example, a target interval of 30 s could be interpreted as a target average waiting time of 18 s.

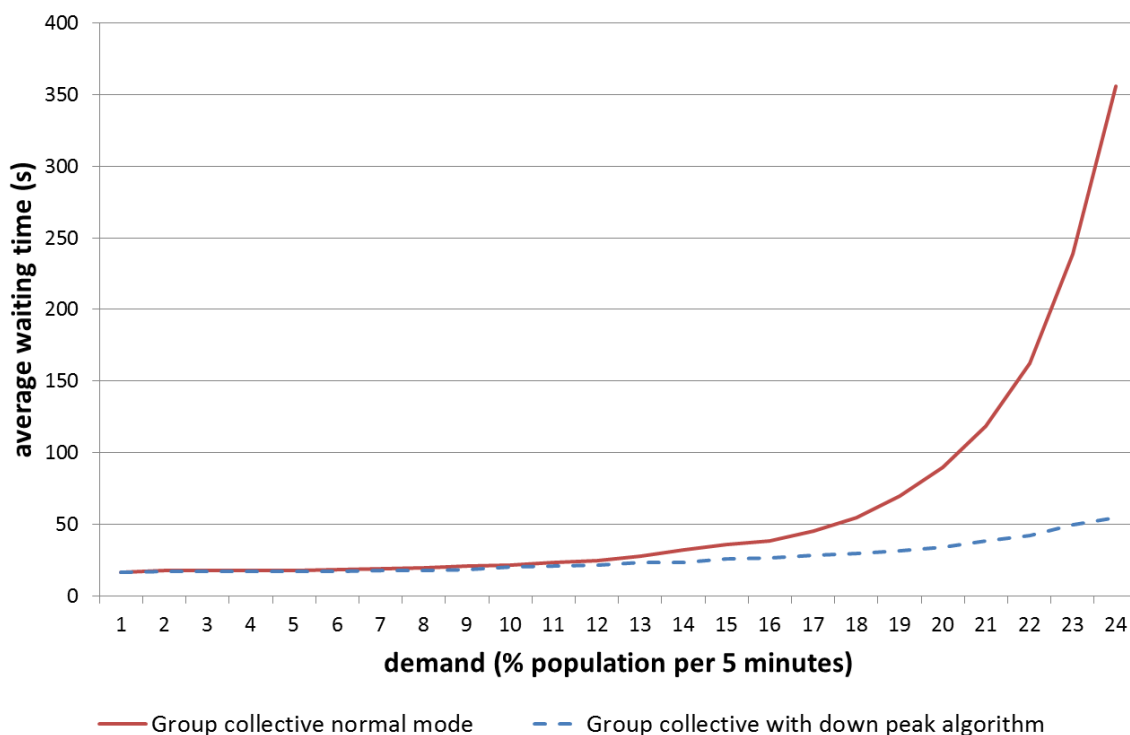
## 7. TRAFFIC CONTROL SYSTEM TESTING

Most traffic control systems have strengths and weaknesses; the step profile is a good way of testing dispatching strategies, which do not necessarily perform consistently across a range of traffic intensities and traffic split (incoming, outgoing, interfloor).

### Example 5 Testing traffic control system performance across a range of traffic intensities

Weaknesses in the management of outgoing traffic can often be observed in buildings where people are attending a large meeting or event with a fixed end time.

Repeat Example 3 with 100% outgoing traffic. Run the simulation with a group collective dispatcher with and without the application of a down peak algorithm.



**Figure 10 Comparison of average passenger waiting times across a range of passenger demands**

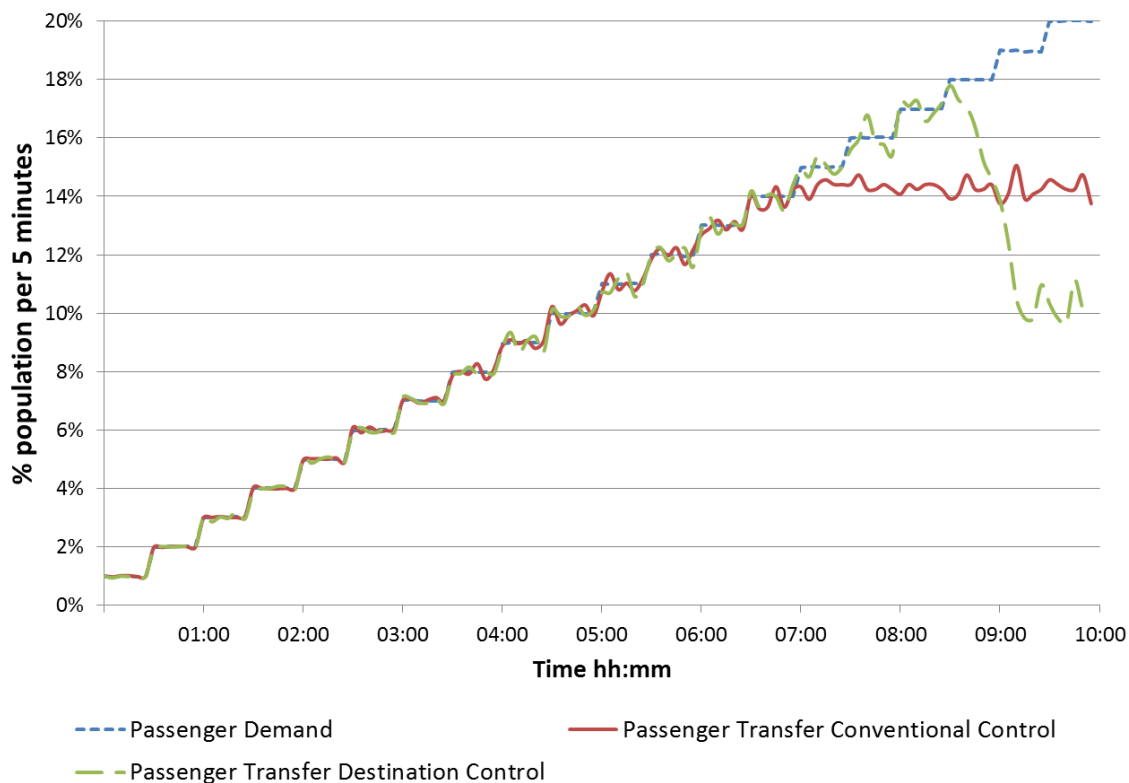
The group collective algorithm is based on allocating the “nearest car”, which is a simple, but effective way of minimising system response time. This strategy works reasonably until demand exceeds handling capacity. At this point, a lack of handling capacity is the problem. The down peak algorithm [1] reduces the average number of stops per round trip, which reduces the round trip time and increases the handling capacity. The increased handling capacity results in lower waiting times.

### Example 6 Example of traffic control system collapse in saturation

It is well understood that destination control boosts up-peak handling capacity. However some destination control installations perform poorly where the demand exceeds the boosted handling capacity.

This is easiest to illustrate by extending Example 3 and plotting passenger transfer (people who have loaded the lifts) with demand. Figure 11 shows up-peak demand increasing to a point where it exceeds the handling capacity of a conventional system (in this case approximately 14%). Queues will be forming, but the system still delivers 14% handling capacity. The up-peak handling capacity of the sample destination control system is greater (in this case approximately 17%). However when the demand exceeds the boosted handling capacity the system manages saturation poorly, and its handling capacity drops to approximately 10%.

This collapse in handling capacity has been observed in real buildings. It happens because the dispatcher concept does not consider the saturation scenario. There are a number of ways of to address this.



**Figure 11 Increasing demand followed by passenger transfer until handling capacity reached, showing subsequent collapse of handling capacity in some cases**

For comprehensive testing, the designer should consider all recognised traffic conditions (up-peak, lunch-peak, and down-peak). Scenarios should include multiple entrance floors and special floors such as restaurant and conference levels.

## 8. OTHER CONSIDERATIONS

### Multiple runs

In most cases it is best to carry out multiple (typically ten) simulation runs. This provides a greater sample size with which to generate results that are statistically significant.

Multiple runs can be achieved by using different random number seeds with the same arrival rates and destination probabilities. The demand is the same, but passengers are arriving at slightly different times. It can be helpful to think of this as modelling different days of the week, Monday, Tuesday, Wednesday, etc. Results can then be averaged for all the simulations.



Without multiple simulations, the chance element in simulation means that changing a parameter, such as speed or door operating times can sometimes lead to performance results getting worse when it would be expected for them to improve (or vice versa). For example, if doors times are changed to be slightly slower, in one simulation a passenger may catch a lift which they otherwise would have missed. This may impact results in one simulation run, but if multiple simulations are performed the advantage of the improved door times will be demonstrated.

The smaller the variation, the greater number of simulations will be required. For example, if door times are improved by 0.1s, it may be necessary to run fifty simulations to demonstrate that average waiting time is also improved, if only by a fraction of a second.

## 9. DISCUSSION

Simulation is a powerful tool which overcomes the limitations of round trip time calculations. However it introduces many complexities to do with real operation, which are not captured in round trip models. Simulations applying a constant traffic template are useful for understanding the relationship between round trip time calculations and simulation; result correlate well if the input assumptions are consistent. Simulations with the step profile provide a better understanding of how lift systems perform across a range of traffic intensities. Simulations based on traffic surveys provide more realistic estimates of how planned lift installations will operate, and the basis for a better assessment of the value of different technologies.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Traffic Patterns in Hotels and Residential Buildings

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### INTRODUCTION

Traffic patterns in office buildings are quite well-known – there is an up-peak in the morning, a mixed lunch-hour traffic peak and a down-peak in the evening. Lift planning and selection criteria for offices are based on the morning up-peak and lunch-hour traffic. The traffic patterns of hotels and residential buildings, however, have not been discussed much publicly. One reason is that in hotels and residential buildings traffic is expected to depend on cultural and regional issues more than in offices. At the moment, global hotel chains have their own standards for planning lifts, and these standards are mostly based on two-way traffic. This paper gathers together the existing lift-planning practices and selection criteria for hotels and residential buildings. In addition, measured daily traffic profiles of hotels and residential buildings are introduced.

### CURRENT LIFT-PLANNING PRACTICES

**Selection of hotel lifts.** Major hotel chains such as Accor, Hilton, Hyatt, Marriott, Four Seasons, Starwood, Ritz-Carlton, and Radisson have their own standards for vertical transportation. The type of the hotel affects the population estimation. For example, an urban city hotel has less people per room than a holiday resort hotel. Strakosch [1] has already introduced population criteria for hotels and motels suggesting the density of 1.5–1.9 guests per room. These are quite in line with the hotel chain design criteria. In some guidelines, the maximum number of guests is counted from the number of beds or room keys. The hotel guidelines are summarized in Table 1. Modern guidelines give their criteria according to the hotel star rating, and use passenger Waiting Times (WT) and Times to Destination (TTD) instead of lift Interval.

For low-rise hotels with less than 10 floors, the guidelines give rules of thumb or tables to select the number and the speed of guest lifts. The number of lifts is roughly defined by the number of rooms where one additional lift is required for every additional 100 guest rooms. CIBSE, however, recommends one lift per 100 hotel guests [2]. In four to five-star hotels, the rated load for passenger lifts is commonly 1 600kg with 1 100 mm wide centre-opening doors, and the load of 1 275kg is accepted as a minimum. In low-rise hotels of fewer than 10 floors, smaller loads, e.g. 800–1 000kg can be used for guest lifts.

According to the hotel standards, the lift speed is defined by the number of floors and population. In Fig. 1, the speed values of the guidelines are shown by data points. An equation that fits well to the guideline values is

$$v = (s-1)*H/T. \quad (1)$$

where the speed is denoted by  $v$ , with the minimum value of 1m/s. The speed depends on the number of the floors,  $s$ , and the floor height,  $H$  (here 3m). The constant,  $T$ , corresponds to the nominal travel time, with the value of 20s. The speed curve of Eq. 1 is also shown in Fig. 1.

Table 1. Design guidelines for hotel guest lifts according to hotel star rating.

Hotel rating	HC	WT	TTD	Density	Rated car load
	(%/5 min)	(s)	(s)	(guests/room)	kg
★★★★★	12-16	20-40	70-90	1.7-1.8	1 600
★★★★	12-14	30-45	70-90	1.5-1.8	1 600
★★★	12	30-45	90-120 <sup>1</sup>	1.3-2	1 275

For luxury or tall hotels, the selection of guest lifts is based on two-way traffic analysis. Collective control is recommended, but also Destination Control is mentioned in the latest guidelines. Handling Capacity (HC) should exceed 12% in five minutes. In resort hotels and motels, Handling Capacity of 10% in five minutes is accepted. In a five-star hotel, average waiting times should stay below 30s, when in hotels with lower ratings even 45s waiting times are accepted. The given values for Times to Destination are quite short, the maximum being 90s. Normally, a 40% car load factor is assumed when guest baggage is carried in the same lift, although up to a 55% value is allowed. Service is usually handled with separate lifts with, e.g., 1800kg load. The number of service lifts is roughly 50-75% of the number of guest lifts. For transporting large or heavy items, freight lifts up to 3 000kg with speeds of 0.3 –0.5m/s are used. If there are parking floors in the hotel, for security reasons it is good to have distinct elevators which serve the traffic between the parking floors and the hotel lobby.

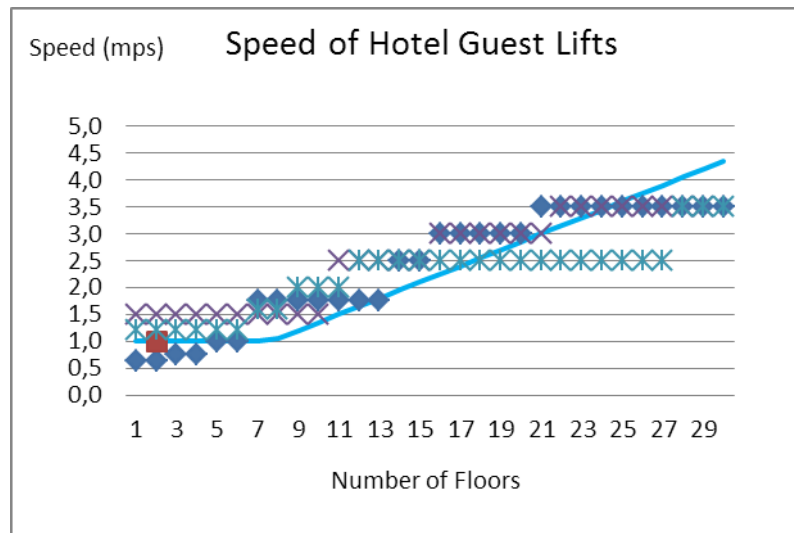


Figure 1. Selection of hotel guest lift speed according to the number of floors (data points refer to the values of different hotel chains, and the solid curve is plotted from Eq. 1).

**Lift selection for residential buildings.** In selecting lifts for low rise apartment buildings, the best practice is to follow local standards. Lifts are mainly needed for the residents, and parking floors can be served directly by the same lifts. In tall buildings, where there are frequent moves in and out, an additional service lift is needed. In high-rise serviced apartments with maids, more than one service lift may be needed. The selection criteria approach hotel criteria. The rated loads of residential lifts vary from 320 to 1000kg. The rated speed can be lower than in hotels with the nominal travel time of 30s [3]. In Equation (1), the value of 30 instead of 20 can be used for the constant  $T$ .

The population estimation is based on the number of bedrooms, and depends much on the culture. Barney suggests 1.5–2 persons in the first bedroom, and 0.5-2 persons for further bedrooms [3]. Strakosch suggests 20m<sup>2</sup> of net area per person when the layout and utilization of residential floor is unknown, or 1.5-2 persons per bedroom [1].

Table 2. Practices with residential passenger lifts.

Residential	HC	WT range	TTD range	Density	Car load
	(%/5 min)	(s)	(s)	(guests/room)	kg
Serviced Apartments	10-12 <sup>1</sup>	30-45	90-120	1.8/first bedroom + 1.4*no of additional bedrooms	1150-2000
High-rise (>10 floors)	7.5-10 <sup>1</sup>	30-60	90-150 <sup>1</sup>	1.8/first bedroom + 1.2*no of additional bedrooms	1000-1 600
Low-rise (< 10 floors)	5-7.5	35-70	90-120	2/first bedroom + 1*no of additional bedrooms	320-1 275

Handling Capacity requirements in residential buildings currently vary between 5–9% in five minutes. Thus, lift capacity or the number of lifts is smaller than in hotels. With fewer lifts, Interval and passenger Waiting Times become longer. The Waiting Time requirement varies between 30 and 60s, and Time to Destination is between 90 and 150s due to the lower lift speeds.

## MEASURED TRAFFIC PATTERNS

**Measurement methods.** The people flow in passengers per 5 minutes was measured in four hotels and four residential buildings in six countries: Finland (FI), France (FR), Egypt (EG), Hong Kong (HK), Singapore (SI), and UAE (DU). The measured hotels had four to five-star ratings, and were from 10 to 55 floors tall while the measured residential buildings had 15 to 50 floors. In all the lift groups, a conventional full collective control system was used. The population in the hotels was estimated from the number of rooms with 1.7 person occupancy per room, and from the number of available room keys. In apartment buildings, the population was calculated from the rooms using the rules of Table 1. By dividing the measured arrival rates by the population, the relative arrivals rates in % per 5 minutes were obtained. The number of people using the lifts was measured and analyzed in three different ways:

- 1) The traffic was measured with a pen and paper method, with an observer sitting in the lift lobby and marking down the number of incoming and outgoing passengers. The times of each entry were written down with one minute accuracy. People in residential buildings in Espoo, Finland and Singapore were counted from 7am to 7pm, and from 8am to 8pm for the hotel buildings in Singapore. All the measured days were normal weekdays. The population in the apartment building in Finland was about 100 persons and in Singapore about 400 persons. The population of the hotel in Singapore was about 700 persons.
- 2) Lift Traffic Analyzer (LTA) was connected to the control system to measure certain signals: lift starts, landing calls, door states, and photocell signal cuts from the car door openings [4]. The number of people using the lifts on all floors was analyzed from the photocell signals for the whole day. The photocell signal, however, does not provide information of whether a passenger enters or exits the car. With the LTA, the traffic of a hotel in Helsinki, Finland, and a residential building in Marseille, France was measured. The hotel had 170 guests and the apartment building 500 inhabitants.
- 3) The most comprehensive people flow estimation was obtained from the group control which can measure the number of entering and exiting passengers, and also the inter-floor traffic on upper floors. The people were counted by the TMS9000 control system [5,6] for the whole day in Cairo, Egypt, in Dubai, UAE, and in Hong Kong. The estimated population in the hotel in Cairo was 1 240 persons, and in Dubai 490 persons. The residential building in Hong Kong had 760 inhabitants.

**Measurement results.** The traffic is mostly two-way in both building types, but traffic intensity is higher in hotels. The relative arrival rates of the hotels are shown in Fig. 2. There are two traffic

peaks: one is in the morning when people have breakfast and check out, and the other is in the evening when people check in and have dinner. The widths and the heights of the peaks as well as the portions of incoming, inter-floor and outgoing components vary according to the building layout and the culture. The inter-floor traffic is caused by the common floors including, e.g., gyms, restaurants, and business centers. In the measured hotels, the maximum arrival rate was 9.5% of the population in five minutes.

Among the four residential buildings, the maximum traffic peak was 5.7% in five minutes as can be seen in Fig. 3. In the residential buildings, there is a down-peak in the morning, somewhat more incoming traffic in the evening, and only little inter-floor traffic during the day.

For planning purposes, the individual building measurements were combined into average and worst-case profiles. For the average profile, the average of all arrival rates were calculated, and, for the worst-case profile, the maximum arrival rate of the four measurements for each interval was selected. In Fig. 4 and Fig. 5, the average profile divided in traffic components, and the worst-case profiles with dashed lines are shown. Numerical values of the resulting profiles are shown in Appendix 1. The portions of the incoming, inter-floor and outgoing components are averages of the four building measurements, and are given in per cent of the arrival rate.

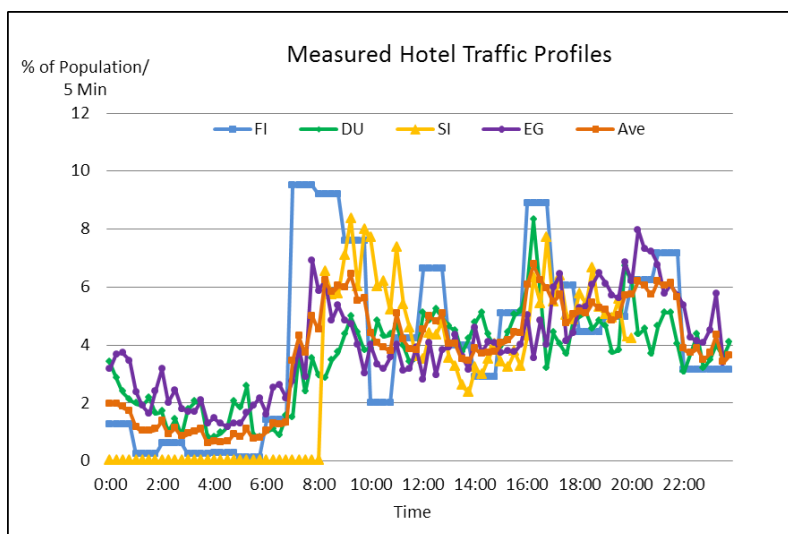


Figure 2. Four measured and the average daily traffic profiles of hotels.

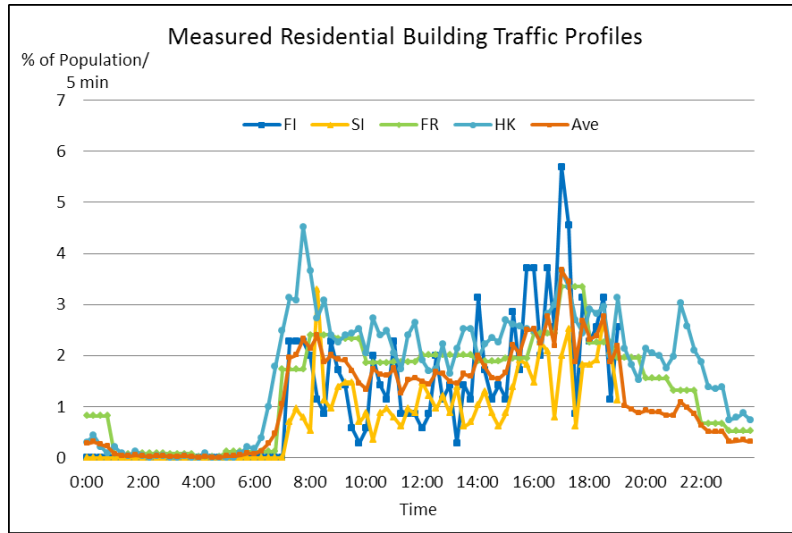


Figure 3. Four average daily residential buildings.

measured and the traffic profiles of

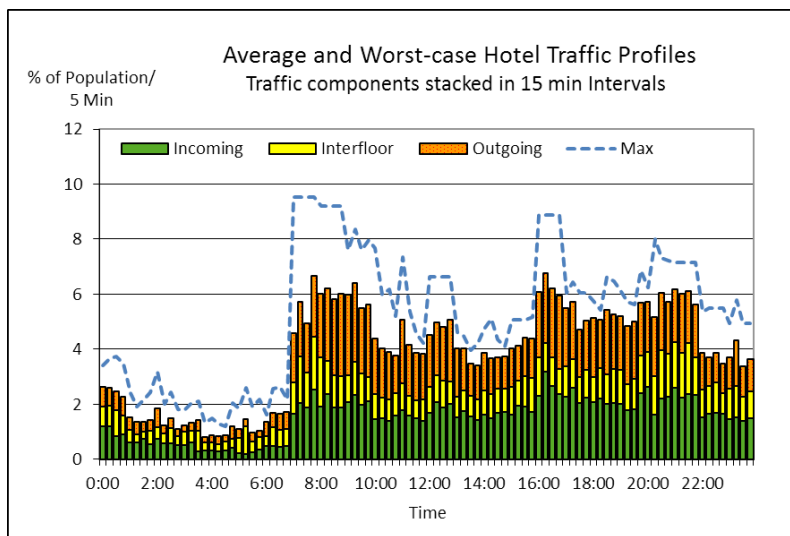


Figure 4. Average daily traffic divided in components, and the worst-case profile (dashed line) of hotels.

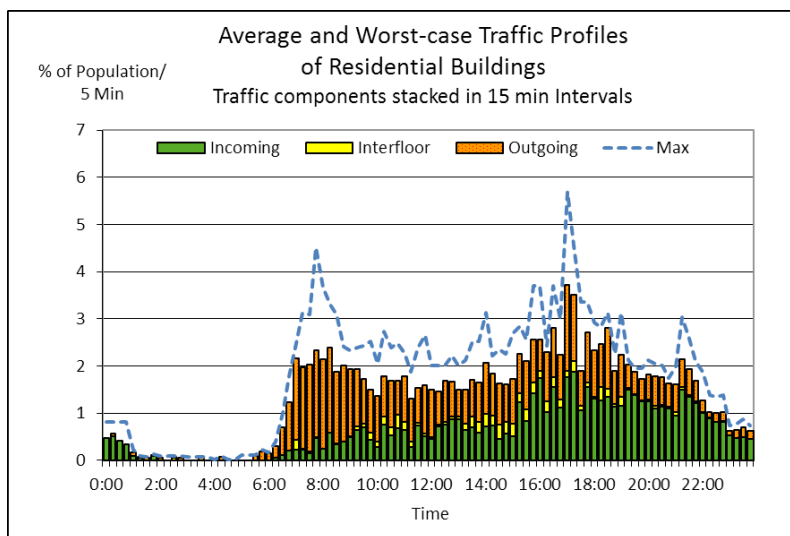


Figure 5. Average daily traffic divided in components, and the worst-case profile (dashed line) of residential buildings.

## DISCUSSION

In this paper, the planning standards of passenger lifts in hotels and residential buildings were discussed. If the planning criteria are compared with the measured traffic profiles in the buildings, the assumption of using two-way traffic in the analysis seems to have a firm basis.

The measured hotel profiles as well as the residential profiles resemble each other although the measurements were made in different parts of the world. Measured traffic was heavier in the hotels compared to the apartment buildings. In hotels the traffic is mostly two-way, but also a little inter-floor traffic. Arrival rates are higher in the morning and in the afternoon during check-in. In residential buildings the traffic is two-way. There is, however, more down traffic in the morning, and in the evening more incoming traffic.

The average profile of the four measurements in each building type was calculated. Averaging flattens the peaks since they occur at slightly different times. That is why the worst-case profile with maximum intensities was formed. The measured maximum peak in the four to five-star hotels was 9.5% in five minutes, which is below the planning standard of 12% in five minutes. The hotels probably were not fully booked during the measurement, and the population was thus below the planned population. The maximum peak in the measured residential buildings was 5.7% in five minutes that is in the range of the planning criteria of 5–7% in five minutes.

If the actual population differs from the planned population, the relative arrival rates of Appendix 1 can be rescaled. As an example, if the actual population is 80% of the planned, the relative arrival rates of the appendix can be divided by 0.8. The arrival rates of each traffic component are obtained by multiplying the relative arrival rate by the proportions of the traffic components given in the table.

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Appendix 1. Daily traffic patterns of hotel and residential buildings

Time	Hotel					Residential				
	Traffic components			Arrival rate		Traffic components			Arrival rate	
	Incoming	Inter-floor	Outgoing	Average	Worst-case	Incoming	Inter-floor	Outgoing	Average	Worst-case
[Hh:mm]	[%]	[%]	[%]	[% / 5 min]	[% / 5 min]	[%]	[%]	[%]	[% / 5 min]	[% / 5 min]
0:00	44	26	30	2.0	3.4	100	0	0	0.3	0.8
0:15	44	27	29	2.0	3.7	87	1	12	0.3	0.8
0:30	34	34	32	1.8	3.7	100	0	0	0.3	0.8
0:45	44	28	28	1.7	3.5	100	0	0	0.2	0.8
1:00	42	27	31	1.2	2.4	54	1	45	0.1	0.2
1:15	44	22	34	1.0	1.9	79	1	20	0.0	0.1
1:30	50	19	31	1.0	2.2	66	1	33	0.0	0.1
1:45	39	30	31	1.1	2.4	85	1	14	0.0	0.1
2:00	41	23	36	1.4	3.2	61	1	38	0.0	0.1
2:15	45	28	27	0.9	2.0	0	0	100	0.0	0.1
2:30	39	35	26	1.1	2.4	0	59	41	0.0	0.1
2:45	45	26	29	0.8	1.8	61	1	38	0.0	0.1
3:00	41	37	22	0.9	1.8	0	0	100	0.0	0.1
3:15	45	29	26	1.0	2.0	0	0	100	0.0	0.1
3:30	22	48	30	1.1	2.1	63	1	36	0.0	0.1
3:45	40	32	28	0.6	1.3	0	0	100	0.0	0.1
4:00	36	34	30	0.6	1.5	0	0	100	0.0	0.0
4:15	35	28	37	0.6	1.3	46	1	53	0.0	0.1
4:30	36	36	28	0.7	1.2	0	0	100	0.0	0.0
4:45	34	27	39	0.9	2.0	0	0	100	0.0	0.0
5:00	21	50	29	0.8	1.8	0	0	100	0.0	0.1
5:15	14	66	20	1.1	2.6	0	0	100	0.0	0.1
5:30	27	39	34	0.7	1.9	0	0	100	0.1	0.1
5:45	32	43	25	0.8	2.2	0	0	100	0.1	0.2
6:00	35	25	40	1.0	1.6	0	0	100	0.1	0.2
6:15	29	38	33	1.3	2.6	20	1	79	0.1	0.4
6:30	29	35	36	1.2	2.6	16	1	83	0.3	1.0
6:45	29	34	37	1.3	2.2	16	1	83	0.5	1.8
7:00	36	24	40	3.4	9.5	12	7	81	1.1	2.5
7:15	35	30	35	4.3	9.5	10	3	87	2.0	3.1
7:30	38	25	37	3.7	9.5	7	3	90	2.0	3.1
7:45	38	28	34	5.0	9.5	20	1	79	2.3	4.5
8:00	32	30	38	4.5	9.2	10	2	88	2.1	3.7
8:15	36	24	40	6.2	9.2	24	1	75	2.4	3.3
8:30	30	25	45	5.8	9.2	17	3	80	1.9	3.1
8:45	29	24	47	6.0	9.2	19	1	80	2.0	2.4
9:00	32	22	46	6.0	7.6	25	2	73	1.9	2.3
9:15	34	24	42	6.4	8.3	33	5	62	1.9	2.4
9:30	34	25	41	5.5	7.6	39	6	55	1.7	2.4
9:45	35	22	43	5.6	8.0	29	11	60	1.5	2.5
10:00	30	28	42	4.4	7.7	20	10	70	1.3	2.0
10:15	34	25	41	4.0	6.0	42	10	48	1.7	2.7
10:30	33	27	40	3.9	6.2	31	11	58	1.6	2.4
10:45	39	27	34	3.8	5.2	40	18	42	1.6	2.5
11:00	32	26	42	5.1	7.4	36	10	54	1.7	2.3
11:15	35	24	41	4.2	5.4	22	9	69	1.3	1.9



11:30	36	23	41	3.8	4.6	48	5	47	1.5	2.4
11:45	35	24	41	3.8	4.2	31	6	63	1.6	2.7
12:00	35	25	40	4.5	6.6	30	3	67	1.5	2.0
12:15	39	24	37	5.0	6.6	49	3	48	1.4	2.0
12:30	37	25	38	4.8	6.6	44	5	51	1.7	2.0
12:45	37	21	42	5.1	6.6	52	4	44	1.6	2.2
13:00	36	23	41	4.0	4.6	57	5	38	1.5	2.0
13:15	41	24	35	4.0	4.5	42	11	47	1.5	2.1
13:30	42	26	32	3.5	4.0	41	14	45	1.6	2.5
13:45	40	25	35	3.4	4.2	35	15	50	1.6	2.5
14:00	40	27	33	3.9	4.8	34	14	52	2.0	3.1
14:15	39	28	33	3.7	5.1	39	13	48	1.8	2.2
14:30	43	28	29	3.7	4.4	27	20	53	1.6	2.3
14:45	43	28	29	3.7	4.1	35	17	48	1.5	2.3
15:00	38	29	33	4.0	5.1	29	16	55	1.7	2.7
15:15	45	26	29	4.1	5.1	54	10	36	2.2	2.8
15:30	41	29	30	4.4	5.1	39	13	48	2.0	2.6
15:45	37	32	31	4.4	5.2	55	10	35	2.5	3.7
16:00	36	27	37	6.1	8.9	68	7	25	2.5	3.7
16:15	45	20	35	6.8	8.9	44	11	45	2.2	2.4
16:30	40	22	38	6.2	8.9	55	8	37	2.8	3.7
16:45	37	22	41	5.9	8.9	50	8	42	2.2	3.0
17:00	39	25	36	5.5	6.1	47	5	48	3.7	5.7
17:15	42	24	34	5.7	6.5	53	7	40	3.4	4.6
17:30	40	26	34	4.7	6.1	55	6	39	1.9	3.4
17:45	42	25	33	5.0	6.1	57	4	39	2.7	3.4
18:00	38	23	39	5.1	5.8	55	3	42	2.3	2.9
18:15	41	26	33	5.1	5.4	51	12	37	2.4	2.8
18:30	35	25	40	5.4	6.6	47	8	45	2.8	3.1
18:45	36	28	36	5.3	6.5	60	4	36	1.9	2.3
19:00	36	29	35	5.2	6.1	51	9	40	2.2	3.1
19:15	35	24	41	4.8	5.7	74	2	24	1.0	2.1
19:30	34	27	39	5.0	5.6	73	2	25	0.9	2.0
19:45	40	28	32	5.7	6.9	71	3	26	0.9	2.0
20:00	44	26	30	5.7	6.2	68	3	29	0.9	2.1
20:15	36	28	36	6.2	8.0	62	3	35	0.9	2.0
20:30	38	26	36	6.0	7.3	64	3	33	0.9	2.0
20:45	40	25	35	5.7	7.2	67	3	30	0.8	1.8
21:00	43	25	32	6.2	7.2	58	5	37	0.8	2.0
21:15	39	26	35	6.0	7.2	69	4	27	1.1	3.0
21:30	41	27	32	6.1	7.2	69	3	28	1.0	2.6
21:45	42	24	34	5.6	7.2	71	3	26	0.9	2.1
22:00	42	24	34	3.9	5.4	79	2	19	0.6	1.9
22:15	45	25	30	3.7	5.5	87	2	11	0.5	1.4
22:30	44	26	30	3.9	5.5	79	1	20	0.5	1.3
22:45	47	21	32	3.5	5.5	79	4	17	0.5	1.4
23:00	39	27	34	3.7	4.9	84	1	15	0.3	0.7
23:15	37	24	39	4.3	5.8	72	1	27	0.3	0.8
23:30	40	24	36	3.4	4.9	70	1	29	0.3	0.9
23:45	40	25	35	3.6	4.9	71	1	28	0.3	0.7

# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## Cabin Ventilation, Code Requirements and Experimental Results

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**Abstract.** If a lift cabin is built in accordance with the ventilation requirements specified in EN 81, it is almost universally assumed that the cabin is adequately ventilated. Experiments were conducted to confirm this assumption.

The experiments involved simulated entrapments of passengers for a period of 30 minutes in lifts installed at the Dubai, United Arab Emirates. Air quality was monitored during the entrapments. Several of the experiments had to be stopped before completion of 30 minutes as the air quality had degraded to levels considered to be unhealthy by occupational health authorities.

The experimental methods and their results are reported.

Recommendations for improved cabin ventilation are made based on the experimental results.

### INTRODUCTION

If a lift cabin is built in accordance with the ventilation requirements specified in EN 81, it is almost universally assumed that the cabin is adequately ventilated. Experiments were conducted to confirm this assumption.

The experiments involved simulated entrapments of passengers for a period of 30 minutes in lifts installed in Dubai, United Arab Emirates. Air quality was monitored during the entrapments. Several of the experiments had to be stopped before completion of 30 minutes as the air quality had degraded to levels considered to be unhealthy by occupational health authorities.

The experimental methods and their results are reported.

Recommendations for improved cabin ventilation are made based on the experimental results.

### BACKGROUND

EN 81-1 prescribes the following minimum ventilation requirements [1].

1. Cabins must have ventilation perforations in the upper and lower portion of the cabin.
2. The area of the perforations in the upper portion of the cabin must equal 1% of the cabin floor area.
3. The area of the perforations in the lower portion of the cabin must equal 1% of the cabin floor area.
4. The gaps around the car door can account for up to 50% of the required area.

EN81-1 makes no reference to forced ventilation (car fans).

The ASME A17.1 requires the following minimum ventilation (ASME, 2007) [2]:

1. Ventilation openings must be located within 300mm above the floor and in the space 1825mm above the floor. 50% of the openings must be in the lower portion of the walls and 50% must be in the upper portion.
2. The total natural ventilation must be equal to 3.5% of the floor area.
3. All of the gap around the doors can be considered.
4. The unrestricted opening around forced ventilation can also be considered.

In the simplest of terms, ASME requires 50% more natural ventilation than EN81-1.

The United Arab Emirates is in the process of developing a lift code. The author was part of the committee developing this code. The code is based upon EN81-1. However, many lifts have been installed according to the code in the country of origin of the lift. Therefore, many lifts are built in accordance with Japanese and Korean codes.

It is common practice in the Middle East for a lift manufacturer to provide an unfinished cabin shell. The interior decoration is provided by local contractors. As a result the only ventilation is from fans and door gaps.

## **INCIDENT**

After filming a video scene, approximately 15 dancers entered a 1275 kg lift. A 1275 kg lift can carry 17 passengers. The dancers continued dancing or jumping in the lift and caused the safety gear to actuate. As a result, the dancers were trapped in the car.

Service technicians arrived on the scene and rescued the passengers in less than 15 minutes. The building was well air conditioned and the lift was in the interior of the building. However, some of the dancers reported that they were suffering from a lack of oxygen and one requested medical treatment. After observation the dancer was released.

When the author was informed of the incident, he dismissed the incident as hyperventilation but suggested that an investigation be started to identify what caused the breathing problems.

## **INVESTIGATION**

The cabin design was reviewed and it was found to be in compliance with EN81-1, the code required by the building specifications. In fact, the natural ventilation exceeded the EN81-1 code by 16.5%.

It was decided that an experiment be conducted with another lift in the complex. The lift was manufactured in accordance with the Jordanian Lift Code. Asian lifts tend to have cabin fans that pump air into the cabin whilst European and American lifts tend to have exhaust fans. This lift had 2 fans that pumped air into the cabin.

The lift was filled to capacity with passengers. The passengers were a mixture of lift technicians and building maintenance personnel. The passengers were given full details of the experiment.

With a technician on the car top, the car was moved to a point between floors and stopped.

This lift was located in a car park and was exposed to the outside air. The experiment was conducted in late March when the temperature was mild, around 22° to 24°C. During the experiment, the wind was blowing at between 10 to 20 kph. The lift was in a common hoistway with another lift.

Air quality was sampled at the start of the experiment and every five minutes during the experiment. Measurements of temperature, relative humidity, carbon monoxide, total volatile organic compounds (TVOC), and, carbon dioxide were taken using a Grey Wolf IQ-610 tool.

After 15 minutes the experiment was terminated because some of the passengers complained that they were feeling bad.

The result was totally unexpected.

It was decided to conduct further experiments on the original lift where the entrapment occurred. In addition, only lift technicians were used as passengers so there would be no fear associated with stopping a lift between floors.

## **Parameters measured**

### **Carbon Dioxide and Carbon Monoxide**

A consulting group, Foster-Miller Inc., produced a report for the US Bureau of Mines titled *Development of Guidelines for Rescue Chambers* [3]. Rescue Chambers are built in mines as places of refuge in case of emergencies. A rescue chamber is a small confined space not unlike a lift car. This report discusses air quality requirements and the origins of the gases found in these chambers.

The two factors that were considered the most critical in Rescue Chambers are Carbon Dioxide and Carbon Monoxide.

The power source of human functions is produced by the oxidation of carbon and hydrogen [3]. Hydrogen is provided by food and oxygen is provided through inhaled air. Water and carbon dioxide are the products of perfect combustion. In a totally closed environment, oxygen would be converted into carbon dioxide until the passengers died of carbon dioxide toxicity or lack of oxygen. Carbon dioxide (CO<sub>2</sub>) is toxic at a level of 50,000 ppm. However, at levels above 1,000 ppm adverse effects are observed. Many researchers believe that these effects are not the result of carbon dioxide but rather a lack of oxygen [3].

Carbon monoxide (CO), although it is commonly associated with faulty heating equipment, is produced in small amounts when breathing. Carbon monoxide bonds more easily to hemoglobin, the oxygen transporting medium of red blood cells, than oxygen. The World Health Organization recommends that the maximum concentration of carbon monoxide not exceed 10 parts per million (ppm) for 8 hours [4].

## **Temperature, Relative Humidity and Apparent Temperature**

Studies have been made of the combined effects of temperature and relative humidity on the human body [5]. An apparent temperature matrix has been published based on this research. Apparent temperatures of 40° C are considered life threatening due to the fact that at this temperature heat exhaustion and heat stroke can occur.

## **TVOC**

The Total Volatile Organic Compounds (TVOC) are human bioeffluents (body odor). Whilst body odor is not toxic, it can be offensive and increase the discomfort level of trapped passengers.

## **EXPERIMENTAL RESULTS**

The experiments involved filling the lift with 15 lift technicians (including the author) and stopping the lift between floors simulating entrapment. A technician was also on the car top who could move the car quickly to a landing and open the doors if needed.

For the first experiment the car fan was operating and the required vent openings were not obstructed. See Table 1.

## Air quality Lift 1: 15 passengers, Vents open, Fan operating

CONDITION	Parameters					
	TEMPERATURE (°C)	RH (%)	Apparent Temperature (°C)	CO (ppm)	TVOC (ppb)	CO <sub>2</sub> (ppm)
			40 = Life-threatening			
Before start	22.8	53.4	23	1.2	154	1105
After 5 minutes	25.6	70	28	1.8	201	3654
After 10 minutes	27.3	69.1	29	2.2	210	3820
After 15 minutes	28.1	74.8	32	2.5	244	4900
After 20 minutes	28.8	69.5	34	2.5	226	4400
After 25 minutes	29.3	71.4	34	2.6	233	4450
After 30 minutes	29.7	69	36	2.6	229	4585

Table 1

All of the measured values increased during the experiment, but none reached a critical level.

In the second experiment the fan was switched off but the vents were unobstructed. See Table 2.

**Air quality Lift 1: 15 passengers, Vents open, Fan **not** operating**

CONDITION	Parameters					
	TEMPERATURE (°C)	RH (%)	Apparent Temperature (°C)	CO (ppm)	TVOC (ppb)	CO <sub>2</sub> (ppm)
			40 = Life-threatening			
Before start	24.7	43.7	24	0.9	15	980
After 5 minutes	26.7	66.4	28	1.6	213	3680
After 10 minutes	28.2	71.6	30	2	231	4235
After 15 minutes	29.4	76.5	35	2.3	254	4176
After 20 minutes	30.6	73.2	38	2.5	249	4780
After 25 minutes	30.5	73.7	38	2.7	256	5150
After 30 minutes	30.9	78.5	41	2.8	306	5410

Table2

After 30 minutes, the Apparent Temperature exceeded the critical level. As all the values were increasing over time, an entrapment of over 30 minutes could be dangerous.

The third experiment involved sealing the required vent openings with tape simulating a cabin with a customer installed interior. The car fan continued to operate. The Apparent Temperature reached life threatening levels after 25 minutes. See Table 3.

## Air quality Lift 1: 15 passengers, Vents sealed, Fan operating

CONDITION	Parameters					
	TEMPERATURE (°C)	RH (%)	Apparent Temperature (°C)	CO (ppm)	TVOC (ppb)	CO <sub>2</sub> (ppm)
			40 = Life-threatening			
Before start	22.8	59	24	1.2	72	1044
After 5 minutes	25.6	79.8	29	2	254	4985
After 10 minutes	27.5	79.8	27	2.7	313	5818
After 15 minutes	28.7	80.1	36	2.9	331	5994
After 20 minutes	29.4	81.7	37	3.1	383	5896
After 25 minutes	30	82.3	41	3.3	430	6789
After 30 minutes	30.5	83.1	42	3.2	492	5888

Table 3

For the fourth experiment the vents remained sealed and the fan was switched off. For ethical reasons, the experiment was terminated after 15 minutes. All of the parameters were increasing and the Apparent Temperature had had reached he life threatening level. See Table 4.



<b>Air quality Lift 1: 15 Passengers, Vents sealed, Fan <b>not</b> operating</b>						
<b>CONDITION</b>	<b>Parameters</b>					
	<b>TEMPERATURE (°C)</b>	<b>RH (%)</b>	<b>Apparent Temperature (°C)</b>	<b>CO (ppm)</b>	<b>TVOC (ppb)</b>	<b>CO<sub>2</sub> (ppm)</b>
			<b>40 = Life-threatening</b>			
<b>Before start</b>	<b>25</b>	<b>53</b>	<b>25</b>	<b>0.9</b>	<b>70</b>	<b>1336</b>
<b>After 5 minutes</b>	<b>28</b>	<b>77.1</b>	<b>33</b>	<b>1.8</b>	<b>258</b>	<b>5417</b>
<b>After 10 minutes</b>	<b>29.4</b>	<b>83.3</b>	<b>36</b>	<b>3</b>	<b>467</b>	<b>7893</b>
<b>After 15 minutes</b>	<b>30.3</b>	<b>85.7</b>	<b>40</b>	<b>4.1</b>	<b>507</b>	<b>8826</b>
<b>Experiment Terminated</b>						

Table 4

## **FINDINGS AND CONCLUSIONS**

The atmosphere in a lift manufactured in complete accordance with EN 81-1, installed in a fully air conditioned building, with the car fan switched off, became life threatening when occupied with a full load of passengers after only 30 minutes. The passengers were not average passengers, they were lift technicians. Members of the public when suddenly trapped between floors in a lift can be expected to respond less calmly to the situation than the technicians. This would most likely result in faster breathing and higher perspiration rates. Both of which accelerate the deterioration of the cabin environment.

Many lifts are installed in buildings without air conditioning and located in tropical and sub-tropical regions where air temperatures exceed 46°C and humidity exceeds 50% (Apparent Temperature 66°C). Even a single person trapped for only a short time is a great risk.

The cabin ventilation requirements in the current codes might need to be revised. More research is needed to determine the appropriate ventilation requirements. Computerized Fluid Dynamics (CFD) software could be used to improve ventilation designs. Perhaps ventilation systems should be viewed as life support systems.

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# 3<sup>rd</sup> Symposium on Lift and Escalator Technologies

## A review of Waiting Time, Journey Time and Quality of Service

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**Abstract.** Waiting Time and Journey Time are generally accepted metrics for Quality of Lift Service. But not all waiting time is equally painful, and other factors do have an impact on perceived quality of service. The psychology of waiting is discussed, and its impact on design considered.

### INTRODUCTION

Waiting Time is generally accepted as the principal metric for Quality of Lift Service. To a lesser extent, Journey Time is also a quality metric.

But other factors also need to be considered depending on the type of lift system e.g. destination systems or multi cabin systems where the waiting time and journey time needs to be defined in more detail.

Destination dispatch systems often provide lower times to destination than conventional systems. However, many such systems accomplish this through longer waiting times and shorter journey times.

In multi cabin systems, including double deck systems, the operation of one cabin affects the operation of other cabins and so there is an impact on passengers' waiting times and journey times.

There are several types of waiting time as well as several types of transit time. These types of time are explored and defined and their effects on quality of service are analyzed.

An examination of the difference between perceived time and real time is conducted.

Additional parameters help us to quantify passenger satisfaction.

Understanding the various types of waiting time and journey time will lead to improved dispatching algorithms.

### BACKGROUND

Considerable research has been conducted on the psychology of waiting in lines. When one thinks of waiting in lines, one most commonly thinks of amusement parks, fast food establishments and grocery stores. However, waiting for a lift is a form of waiting in a line. Two authors are commonly cited in papers on the psychology of waiting; David Maister and Donald Norman.

In 1985, David Maister published a paper, *The Psychology of Waiting Lines* (Maister, 2013) [1]. The following are the key concepts he presented:

1. Occupied time feels shorter than unoccupied time.
2. People want to get started.
3. Anxiety makes waits seem longer.
4. Uncertain waits are longer than known, finite waits.
5. Unexplained waits are longer than explained waits.
6. Unfair waits are longer than equitable waits.
7. The more valuable the service, the longer the customer will wait.
8. Solo waits feel longer than group waits.

Donald Norman published a paper in 2008 that was also titled *The Psychology of Waiting Lines* (Norman, 2013) [2]. Norman presented eight design principles for waiting lines. The principles are as follows:

1. Emotions dominate.
2. Eliminate confusion: Provide a conceptual model, feedback and explanation.
3. The wait must be appropriate.
4. Set expectations, then meet or exceed them.
5. Keep people occupied: Filled time passes more quickly than unfilled time.
6. Be fair.
7. End Strong, start strong.
8. Memory of an event is more important than the experiences.

Many of these sixteen concepts apply to waiting and riding in lifts.

## PSYCHOLOGY AND TIME TO DESTINATION

The time to destination is defined in CIBSE Guide D 2010 as the time from when a passenger either registers a landing call or joins a queue, until the responding lift begins to open its doors at the destination floor and is divided into waiting time and transit time (CIBSE,2010) [3]. See Figure 1.

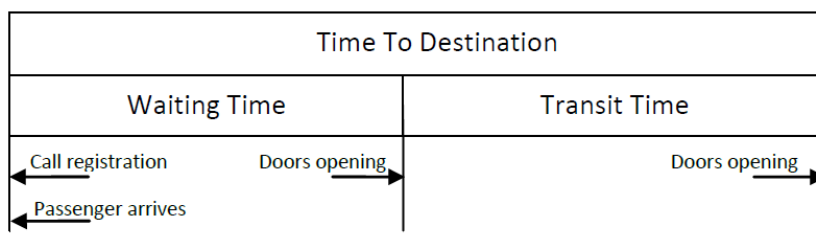


Figure 1

### Waiting Time

The waiting time starts with the call registration. The waiting time includes walking time to the lift and standing time.

For control systems with direct allocation, the passenger, after registering his call and being assigned a lift, must walk to the lift and then stand. For control systems with reallocation and early call announcement a few seconds before the lift arrival, the passenger has to stand and then walk.

The portion of waiting time that is spent walking to the lift is occupied time whilst the time spent standing is unoccupied time. For this paper we will describe the various types of waiting and transit

time as more or less painful. Therefore, occupied waiting time is less painful than unoccupied waiting time.

### Transit Time

During the transit time there could be several stops and trip times. A normal stop has different phases and is shown in Figure 2.

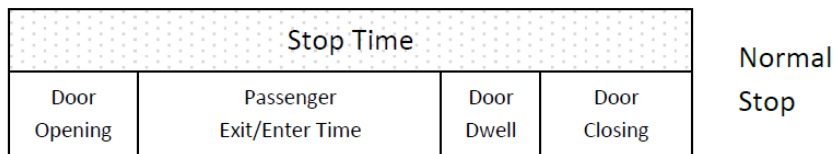


Figure 2

It has been observed that people become impatient when there are many intermediate stops before they reach their destination (Barney & Dos Santos, 1977) [4]. One can conclude that the portion of transit time spent during intermediate stops is more painful than non-stop transit time. Each additional intermediate becomes even more painful.

## LIFT DESIGN

### Psychology of Waiting applies to three General Aspects of Lift Designs

The concepts of the psychology of waiting can be classified in 3 general aspects of lift designs:

#### 1. User Interface:

This includes all the input devices used to call the elevator or to register a destination as well as output devices such as call registered lights or directions to use a particular lift. Additionally, displays and announcements can be used to inform passengers about lift status and service status. The use of special user interfaces and feedback information can affect the options of the lift behavior and dispatcher strategies.

#### 2. Lift Control Functionality:

The lift behavior and the dispatcher functionality should consider the psychology of waiting and the quality of service. Passengers need to be transported in a good and pleasant manner. The dispatcher and the lift performance are responsible for providing the necessary handling capacity that is needed to achieve good Quality of Service.

#### 3. Lift Architecture:

Lift Architecture includes the lobby design, cabin design, fixture design and everything that creates or affects the lift usage environment.

The experience of using the lifts is a combination of the three aspects. See Figure 3.

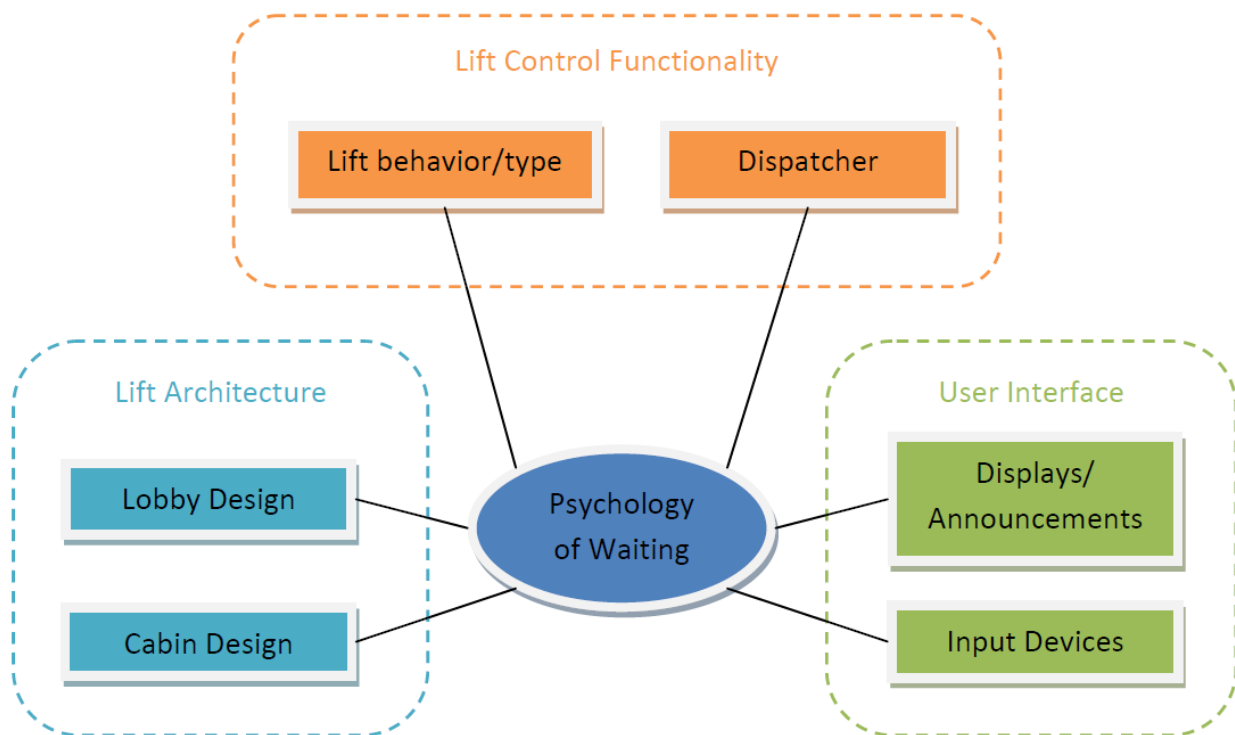


Figure 3

## USER INTERFACE

Good User Interfaces helps to increase passenger satisfaction and improve the perceived Quality of Service. User Interfaces need to be easy for passengers use and understanding.

### Existing Lift User Interfaces

The earliest automatic lifts usually had push buttons that did not include call registered lights. When a passenger registered a call there was no acknowledgement. The lack of acknowledgement creates anxiety because the passenger does not even know if the lift is working. Additionally, the waiting time is uncertain.

Today, virtually all hall push buttons have call registered lights. However, people are often seen pushing a lighted button. The anxiety about whether or not the lift is coming still exists.

Many lift systems from Asia have the Early Call Announcement (ECA) feature where when a hall button is pushed and a fixed lift is allocated (without reallocation), the Hall Lantern illuminates and sounds a chime. This has the advantage of reducing anxiety and removing some of the uncertainty of the wait. The wait is partially explained because the passenger knows that he is waiting for a specific lift. Additionally, part of the wait is occupied by walking to the assigned lift.

Destination dispatch (DD) systems with destination input devices at all floors have the same advantages as ECA systems. However, one can assume that passengers sense they have started their journey when they tell the lift system their destination and the system advises which lift to take. Most people when asked if they like the destination dispatch systems will respond positively. Since emotions dominate, the destination based systems are perceived by the riding public to be superior. Therefore, the same waiting time may seem shorter with a DD system than a conventional system with up and down hall calls.

## **Future Lift User Interfaces**

### **Countdown Indicators**

A countdown indicator could be provided that would display the time remaining until the lift arrives at a landing. Such indicators are common in other transit situations. One often finds a display at subway stations indicating when the next train will arrive.

Such an indicator reduces anxiety and confusion while providing feedback. Additionally, one is occupied watching the display. Maister states that “Occupied time feels shorter than unoccupied time.”

It would be prudent to display a longer than expected time. Such that if the lift is expected to arrive in 10 seconds the indicator should display 15 seconds. One of Norman’s rules is to “Set expectations, then meet or exceed them.”

### **ETA Indicator**

Some Destination I/O devices include an Estimated Time of Arrival (ETA) indicator. The lobby I/O device advises the passenger which lift to take and informs him when it will arrive.

### **Destination Input / Output Devices**

Destination input/output (I/O) device designs vary greatly. Some are simple number pads for destination entry combined with a dot matrix display to indicate the assigned car. Others use more sophisticated Graphic User Interfaces (GUI) such as touch screens similar to those one finds at ATM machines. Whilst both types of I/O devices are equally functional, the use a GUI could be perceived as more pleasurable

The more interesting the device the stronger the start. Norman recommends that we start strong and end strong.

## **LIFT CONTROL FUNCTIONALITY**

### **The Psychology of Waiting; Future Lift Design**

The dispatching algorithm plays a key role in creating a pleasant passenger experience. Many algorithms for destination dispatching systems are based on optimizing time to destination, waiting time and transit time.

#### **Waiting Time vs. Transit Time**

Many destination dispatch systems produce shorter times to destination than conventional systems but do so with longer waiting times. Waiting time is assumed by most to be more “painful” than transit time. This can be explained by Meister’s suggestion that people want to get started and anxiety makes waits seem longer. Once one is in the lift there is no further anxiety about when the lift will arrive and one knows that the journey has started.

If a destination dispatch system had the same Waiting Time and Transit Time as a conventional system, then one might perceive that the DD system had a shorter Journey Time. This is because of less anxiety and the feeling that the journey started with the entry of the destination in the destination input device.

How should a dispatcher choose between the following two options with identical Journey Times?

1. Waiting Time: 30 sec., Transit Time: 30 sec., Journey Time: 60 sec.
2. Waiting Time: 15 sec., Transit Time: 45 sec., Journey Time: 60 sec.

The apparent best choice would be option 2.

However, if option 2 had a waiting Time of 15 seconds and a Transit Time of 50 seconds, would option 2 still be the best option? For example

1. Waiting Time: 30 sec., Transit Time: 30 sec., Journey Time: 60 sec.
2. Waiting Time: 15 sec., Transit Time: 50 sec., Journey Time: 65 sec.

Is the option with a 5 second longer Journey Time and a 15 second shorter Waiting Time the preferred option? The answer would depend on the relative pain of Waiting Time and Transit Time.

Another dispatching choice with identical Journey Times would be the following:

1. Waiting Time: 2 sec., Transit Time: 58 sec., Journey Time: 60 sec.
2. Waiting Time: 10 sec., Transit Time: 50 sec., Journey Time: 60 sec.

One of Norman’s principals is that “Waits must be appropriate”. People expect to wait for lifts. If the wait is appropriate then it is not painful. Therefore, a 10 second waiting time may be no more painful than a 2 second waiting time. Whilst a 58 second Transit Time may well be more painful than a 50 second Transit Time.

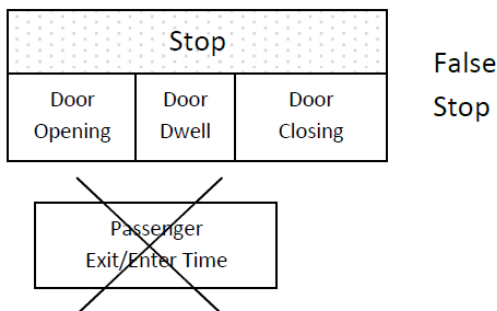
## False Stops and Delays

### Single Car per hoistway single deck

A false stop is a stop of a lift where the doors open and close without passenger transfer as shown in Figure 4.

A false stop could be caused by a passenger registering a landing call but then walking away. A false stop is causing more confusion when it is not explained.

A better option is to avoid false stops. This can be done with machine vision sensor that cancels the landing call if lobby is empty. This reduces stops and avoids confusion.



**Figure 4**



## Multiple Cabin Systems

### Departure Delay and Blind Stops

Multi cabin systems, like double deck systems, can experience Departure Delays because the loading times for the two cabins are not equal.

With two cabins in one hoistway there can be a departure delay if one cabin blocks the way of the other. The cabin blocking the path must move to a new position before the other car can move.

“Blind Stops” occur with Double Deck lifts when a stop is made for one cabin but a stop is not required for the other cabin. This is shown in Figure 5.

The Blind Stop must be explained to the passengers because unexplained waits seem longer than explained waits. Fortune recommends using a display that states “SERVING OTHER DECK” when a blind stop occurs (Fortune, 1995) [5].

Additional departure delays and false stops can be considered by the dispatcher during the cost function and allocation.

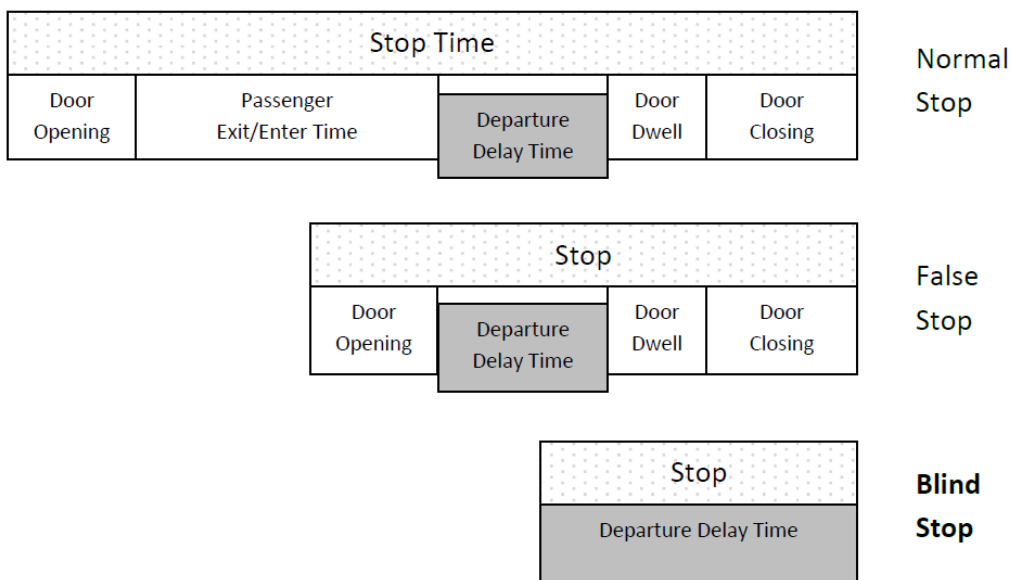


Figure 5

## LIFT ARCHITECTURE

Architectural elements can have a significant effect on the lift experience. The following are some features that should be considered.

**Mirrors:** Mirrors animate passengers to check their hair or clothing while they are waiting and so they are kept occupied (Abilla, 2012) [6]. Also with mirrors in lift cabins appear larger and therefore more comfortable.

**Space:** The size of the lift lobby and the cabin needs to be comfortable for the number of passengers using the lifts at the same time.

**InfoTainment:** InfoTainment can be placed inside the lift cabin or in the lift lobbies. In-car information displays have become very common. One well-known brand is Captivate (Captivate, 2013) [7]. The displays present a mix of news, weather, traffic information and advertising.

The building owner receives revenue from the advertising. However, watching the displays makes Waiting Time and Transit Time also occupied time and therefore it feels shorter than it is.

**Position of Destination Input Devices:** The Destination Input Devices Destination Dispatch Systems are often located outside the lobby. This is shown in Figure 6. Passengers can register their call and a lift is allocated before they enter the lift lobby. The walking time to the lobby is part of the waiting time. This is occupied waiting time and passengers already get started since their journey time starts after the call registration with walking to the lift (lobby).

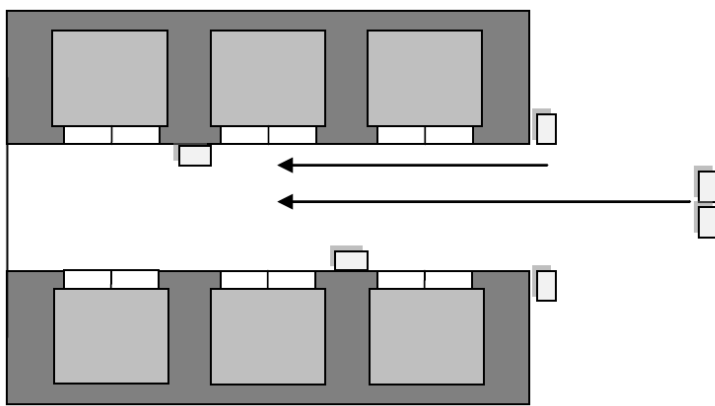


Figure 6

Whenever the waiting time is shorter than the walking time the lift has an additional departure delay as shown in Figure 7. This affects the handling capacity. For passengers already in the cabin the delay is unexplained and uncertain. The Call Dispatcher can avoid such allocations, although in special instances this could be the best allocation.

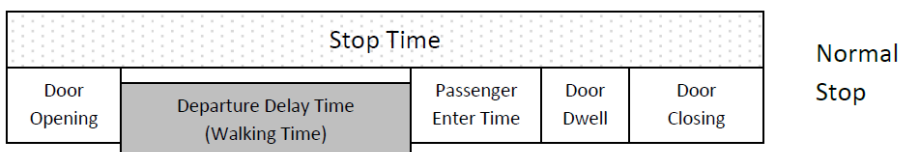


Figure 7. Stop for a single passenger with additional walking time entering a lift

It is helpful if the walking distance is not too far. Passengers forget their car assignment and a second call is generated. A maximum walking distance to the lift lobby of 10m seems to be reasonable.

## FINDINGS AND CONCLUSIONS

There is a need to quantify the perceived pain associated with the different types of Waiting Time and Transit Time. This can only be accomplished through research. Dispatch algorithms can then be created that utilize this knowledge.

The various aspects of lift design affect the perceived pain and need to be considered at quantifying the weight of the pain during the different phases. Depending of the lift appearance, the user interface and the lift control functionality the experience of the lift usage can be different although the duration of waiting time and transit time is the same.

Also cultural issues, special needs, experience of the lift user, and current emotional situation of the passenger affect the perceived quality of service.

Quality of Service is not only the lobby waiting time. It is more than that. It is the total experience the passenger makes during the lift usage.

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