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FOREWORD

It is with great pleasure that we present the proceedings of the 9th Symposium on Lift and Escalator Technologies, 19-20 September 2018, organised by The Lift and Escalator Symposium Educational Trust.

The objective of The Lift and Escalator Symposium Educational Trust is to advance education in lifts, escalators and related technologies. The Trust is a Registered Charity No: 1170947 and is supported by The University of Northampton, The Chartered Institution of Building Services Engineers (CIBSE) and The Lift and Escalator Industry Association (LEIA).

Proceedings from the full conference series (since 2011) are available to download from www.liftsymposium.org. The proceedings are indexed in Scopus as “Symposium on Lift and Escalator Technologies”, starting from the 2015 Symposium. Scopus is the world’s largest abstract and citation database of peer-reviewed literature (scientific journals, books and conference proceedings), see https://blog.scopus.com/about.

The Lift Engineering programme offered at The University of Northampton includes postgraduate courses at MSc/ MPhil/ PhD levels that involves 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.

LEIA is the UK trade association and advisory body for the lift and escalator industry with a membership covering some 95% of the lift and escalator industry. LEIA members supply passenger and goods/service lifts, stairlifts, homelifts, lifting platforms, escalators, passenger conveyors and a range of component parts for such products. LEIA members undertake the maintenance and modernisation of more than 250,000 products falling within the scope of the Association. LEIA provides advice on health, safety and standards matters, promotes education and training especially through its distinctive distance learning programme.

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 title. 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.

Professor Stefan Kaczmarczyk, and Dr Richard Peters
Co-Chairs and Proceeding Editors

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A Retrofit Solution for Remote Lift Monitoring

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Keywords: remote monitoring, internet of things, data, maintenance, asset management

Abstract. A trial has been undertaken on the lifts at Covent Garden station to extract data from the controllers and explore its value for maintenance and asset management. The programmable logic controllers (PLCs) monitor a large amount of information, from discrete signals such as the status of relays, buttons and switches to analogue data for lift car speed and position.

A retrofit monitoring system was designed and installed to facilitate extraction of all available data from the PLCs in real time using a modern lightweight messaging protocol. An original approach to the visual representation of the historical data was developed to enable insights to be gained.

The findings demonstrated that there is value in extracting PLC data for fault diagnosis, improved fault response time and a better understanding of asset operation and condition. This will support a more proactive approach to maintenance and inform whole life asset management.

1 INTRODUCTION

Logging and analysis of data from lifts has occurred since the advent of automatic passenger lifts, originally comprising manual observations in the lobby or lift car including traffic counts and performance parameters such as door operation [1]. In the 1970s after the introduction of the minicomputer, various studies were commissioned by the Building Research Establishment which utilised multi-channel recording equipment to capture data such as intervals and door times for more in-depth analysis of lift systems [2,3,4]. Their use also extended to the provision of call allocation for multi—car systems to minimise total journey time [3] as well as for verification of lift performance. Remote fault identification was also identified as an output of this early work, using telephone lines to alert maintainers in the event of a fault occurring [5].

As technology has continued to advance, the cost and physical size of computers have significantly reduced making onsite data capture more cost effective, and the capabilities have greatly improved. Faster processing speeds, low cost data storage, cloud computing and efficient networking technologies, including wireless, have increased the return on investment in systems for data capture. Data logging has since become available to the average lift operator or maintainer requiring very little investment and is built into many modern controllers [6]. Solid-state storage is significantly more reliable than the early magnetic tape and floppy disks, particularly in harsh environments, making it feasible for equipment to be left in situ with minimal maintenance.

This paper documents a trial to extract data from the lifts at Covent Garden station and explore its value for maintenance and asset management. The controllers are Mitsubishi programmable logic controllers (PLCs) which monitor over 100 discrete signals representing relays, buttons, safety switches, locks, emergency stops and other on/off signals. Lift control mode and analogue lift car speed and position are also available. Remote access to this data is not currently specified for London Underground lift installations or refurbishments.

2 BACKGROUND INFORMATION

As part of the refurbishment of Lifts 1 to 4 at Covent Garden in 2014, a Modbus [7] interface module (Mitsubishi QJ71MB91) was fitted within each of the lift controller cabinets to facilitate data extraction from the PLCs. This would provide flexibility in how the data is processed and stored whilst preventing any unwanted control of the asset by being ‘read only’. The reason for selecting Modbus was that the existing monitoring system for temperature and vibration on other lifts and escalators utilises this protocol, so it would provide compatibility if the decision were made to integrate the data into this system.

The trial was limited to four lifts, however, there is potential to expand the solution to other compatible controllers across the London Underground network comprising around 30 lifts and 110 escalators. Similar solutions are also possible for other controller designs.

Having access to the data from the PLCs could provide a number of advantages. For example, maintainers could be alerted to a fault and given relevant information about it instantly, before it is detected by station staff and reported to the maintainers via the London Underground fault reporting process thereby improving response times. Having the event history available remotely would enable fault finding to be carried out by maintenance staff prior to them leaving their premises, informing which spares should be taken to site and avoiding repeat visits.

As well as providing data for fault detection and diagnosis, there is potential to support predictive maintenance by detecting deviations from normal behaviour and identifying precursors to potential fault conditions using analytics techniques. This could complement condition monitoring data such as vibration, temperature and visual inspections.

Other benefits could include performance and availability monitoring as well as asset usage patterns to inform customer strategy, operational and maintenance planning.

3 STAGE 1 – OFFLINE SOLUTION

The first stage of the trial was to fit a Modbus-compatible data logger on Lift 1 at Covent Garden. This would enable the data from the PLC to be stored on a removable USB drive which could then be analysed to assess its value before progressing to a networked solution. Figure 1 shows the hardware in situ in the lift controller cabinet.

Figure 1 Offline data logger on Covent Garden Lift 1

3.1 System design

The data logger was programmed to poll the status of all the registers in the Modbus module once per second and append the data to a CSV file, with a new file created every hour. This data could then be parsed to extract the status of each individual bit for the discrete signals.

3.2 Findings

To visualise the data effectively, the discrete events were overlaid against the analogue data which gives a clear picture of the behaviour of the asset over time. Figure 2 and Figure 3 show an example of a safe edge fault event which can be seen to have occurred when the lift was at the top landing. The vertical lines represent the change in status of a binary signal, with red being a transition to active state and green being a transition to inactive. In addition to the events from the PLC, faults raised are also listed on the event log, which enables all relevant data to be viewed in chronological order. In this case, the fault was reset locally so no fault was raised to request maintainer attendance.

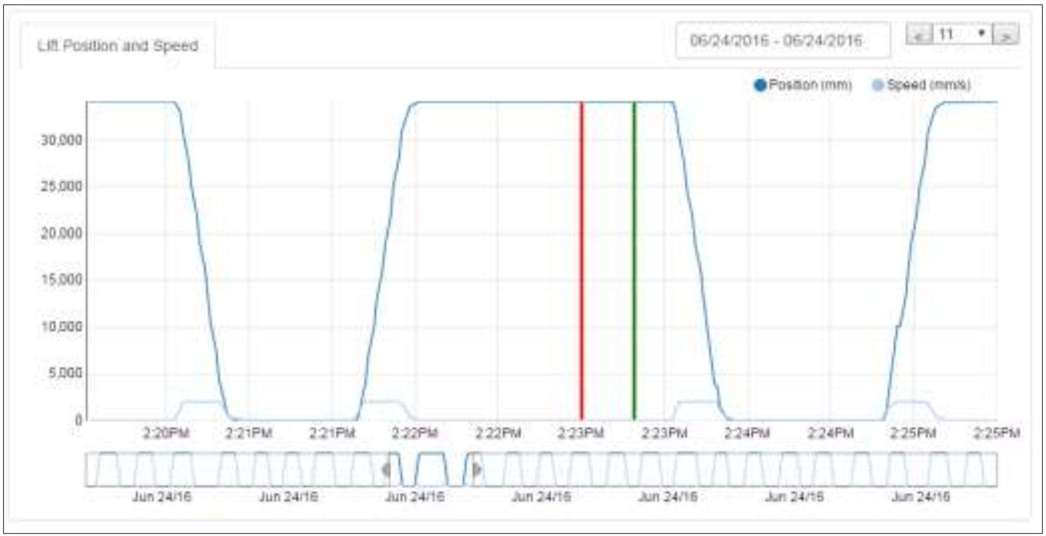
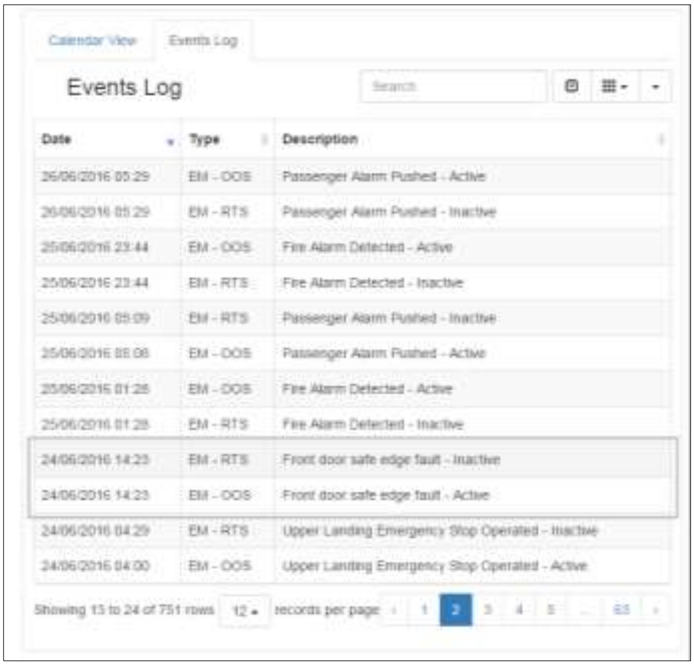


Figure 2 Data visualisation showing safe edge fault event



Date	Type	Description
26/06/2016 05:29	EM - OOS	Passenger Alarm Pushed - Active
26/06/2016 05:29	EM - RTS	Passenger Alarm Pushed - Inactive
25/06/2016 23:44	EM - OOS	Fire Alarm Detected - Active
25/06/2016 23:44	EM - RTS	Fire Alarm Detected - Inactive
25/06/2016 05:09	EM - RTS	Passenger Alarm Pushed - Inactive
25/06/2016 05:08	EM - OOS	Passenger Alarm Pushed - Active
25/06/2016 01:28	EM - OOS	Fire Alarm Detected - Active
25/06/2016 01:28	EM - RTS	Fire Alarm Detected - Inactive
24/06/2016 14:23	EM - RTS	Front door safe edge fault - Inactive
24/06/2016 14:23	EM - OOS	Front door safe edge fault - Active
24/06/2016 04:29	EM - RTS	Upper Landing Emergency Stop Operated - Inactive
24/06/2016 04:00	EM - OOS	Upper Landing Emergency Stop Operated - Active

Showing 13 to 24 of 751 rows 12 records per page ‹ 1 2 3 4 5 ... 63 ›

Figure 3 List of events corresponding to safe edge fault event

The data that was collected using the data logger demonstrated that being able to view historical events alongside reported faults can provide an in-depth view of the asset. This gave confidence that a networked solution on all four lifts was worth pursuing. Some limitations were found with the system, however. The data recorded was subject to latency, compounded at each stage of the path that the data was transmitted. The solution trialled in this case was subject to the rate at which the PLC data was stored to the registers of the Modbus module which was every 100 ms, and this was then sampled at 1 second intervals by the data logger. The analogue data, obtained from an encoder, was subject to a 10ms resolution, which added yet more inaccuracy to the recorded time. These errors are not significant but had to be taken into consideration when analysing the data.

4 STAGE 2 – ONLINE SOLUTION

Once the value of extracting data from the lift controllers had been demonstrated using a data logger on Lift 1, the second stage was to make the data available remotely via a network connection and extend the monitoring to all 4 lifts. This would enable data processing to occur in real-time, providing the ability for alerts to be generated in the event of a fault condition or event of interest if required. A networked solution would also eliminate the manual task of physically visiting site to replace the USB drive and transfer the data which is impractical for a larger scale solution.

4.1 System design

To enable the data acquisition, an NPE X500 M3 industrial computer was installed in the controller of Lift 2 with a connection to the Modbus interface module. The other 3 lift controllers were fitted with a Modbus to Wi-Fi converter, enabling them to transmit data from the Modbus module over a local Wi-Fi network hosted by the X500. This would minimise the amount of hardware and local cabling required and enable the data from all four lifts to be connected to the Wide Area Network via a single 3G connection. The new data acquisition setup allowed the polling of the Modbus module at the maximum frequency available of 10 readings per second. The tenfold increase in time resolution with respect to the offline trial identified more subtle effects such as switch bounce and readings noise. Figure 4 shows the configuration of the networked system.

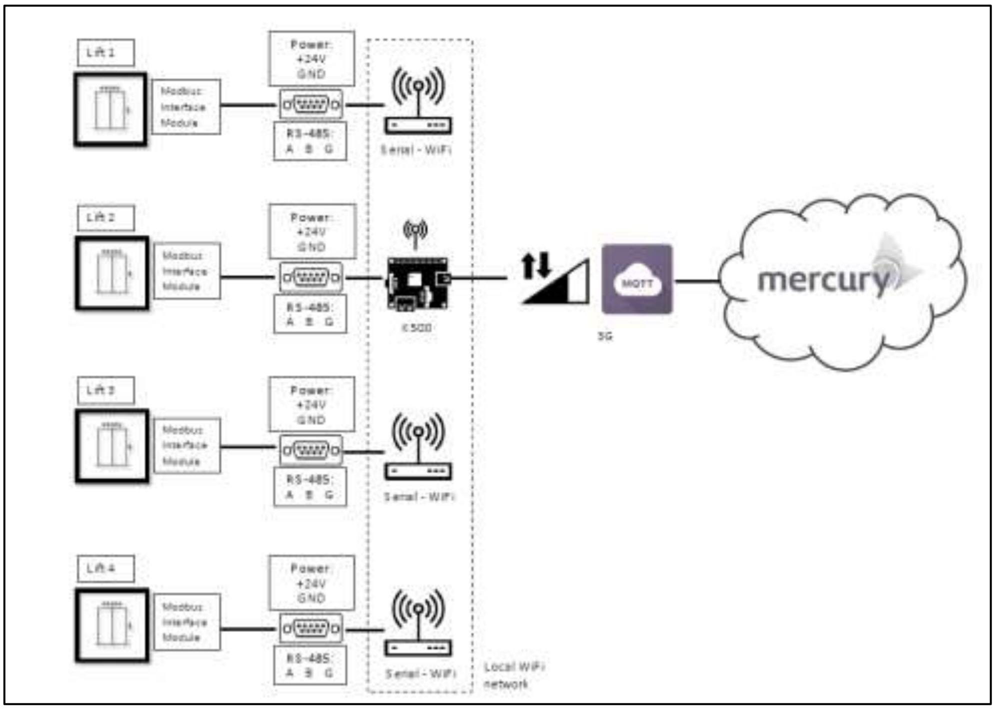


Figure 4 System diagram for online monitoring solution

Using a mobile network with limited availability presented a challenge, especially during peak hours. After appropriate configuration, the X500 would store the messages locally and forward them to the monitoring server when there was available network connection. It was necessary to do some data reduction on site, ensuring that only the changes in the asset state were being sent. This brought the monthly traffic down from 20 GB to 12 GB for all 4 lifts. To ensure data consistency and prevent loss of information, it was decided to use the MQTT protocol. This was encrypted using Transport Layer Security over a Virtual Private Network.

Even after a significant data reduction, a backend was required that could handle the load and allow for the system to scale with ease. The cloud-based asset management platform Mercury [8] developed by Amey Strategic Consulting provided the necessary solution. Utilising RabbitMQ, Apache’s Kafka, Storm and Cassandra, the cloud backend can receive and process thousands of messages per second.

The machine information was aligned with the maintenance records and visualised in Mercury’s frontend for analysis. The X500 unit in situ on Lift 2 is shown in Figure 5.

Figure 5 NPE X500 installed on Lift 2

Following the data analysis from Stage 1 it was decided to explore what additional data could be extracted relating to the doors, as this was identified as the subsystem with the most reliability problems from maintenance records. Due to the latency of the system, the PLC was configured to calculate the entrance and exit door opening and closing times which were stored in additional registers on the Modbus module. Door events were also added as discrete signals to two additional registers, making up six registers defined as follows:

1. Entrance door closing time (16 bits)
2. Entrance door opening time (16 bits)
3. Exit door closing time (16 bits)
4. Exit door opening time (16 bits)
5. Entrance door lock and signal info
    - Bit 0 – Door close output command
    - Bit 1 – Door closed output command
    - Bit 2 – Door open control input
    - Bit 3 – Door safe edge input
    - Bit 4 – Entrance car lock status

- Bit 5 – Upper landing entrance lock status
- Bit 6 – Lower landing entrance landing lock status

6. Exit door lock and signal info (same signals as Register 5)

5 ANALYSIS

Data from the online system was analysed over a nine-month period alongside fault data and discussions with the lift and control system maintenance contractors and station staff. The outcomes of this analysis shall now be discussed.

5.1 Lift availability and utilisation

The immediate benefit of the monitoring system was the ability to profile the assets' utilisation patterns. A quick overview of a day's worth of data showed how the lifts were not being used between midnight and the morning peak. A closer look revealed more subtle differences between the assets. For example, Lift 1 tends to be idle between 00:30 and 05:30, while Lift 4 is idle between 00:00 and 08:15. This can be explained by the fact that Lifts 1 and 2 are closer to the stations entrance and tend to be used more often than Lift 4 which is at the end of the hall. This simple observation can lead to an adjustment of the maintenance schedule to prioritise the more utilised lifts 1 and 2.

5.2 Failure analysis

The discrete alarms and switches are granular enough to show the state of the lift during a fault and often indicate explicitly what the reason was for the downtime. Having all historical data easily available makes it possible to trace back an incident and review the events that led up to it.

Figure 6 shows a fault occurring on Lift 4 on 3rd May 2018 at 14:49. It is immediately flagged up as 'Failed at Lower Landing' with 'Front door NOT open'. A minute and a half later a member of staff put the lift in landing control and took the lift out of service. Tracing back the asset state over the previous 12 hours shows two intermittent 'Failed at Lower Landing' events with the longer of the two lasting 20 seconds, accompanied by a 'Lower landing front locks open' event. This indicates a developing problem with the lower landing doors mechanism. The maintenance staff attending the fault reported that the lower landing entrance door was out of alignment with the car door skate and was realigned.

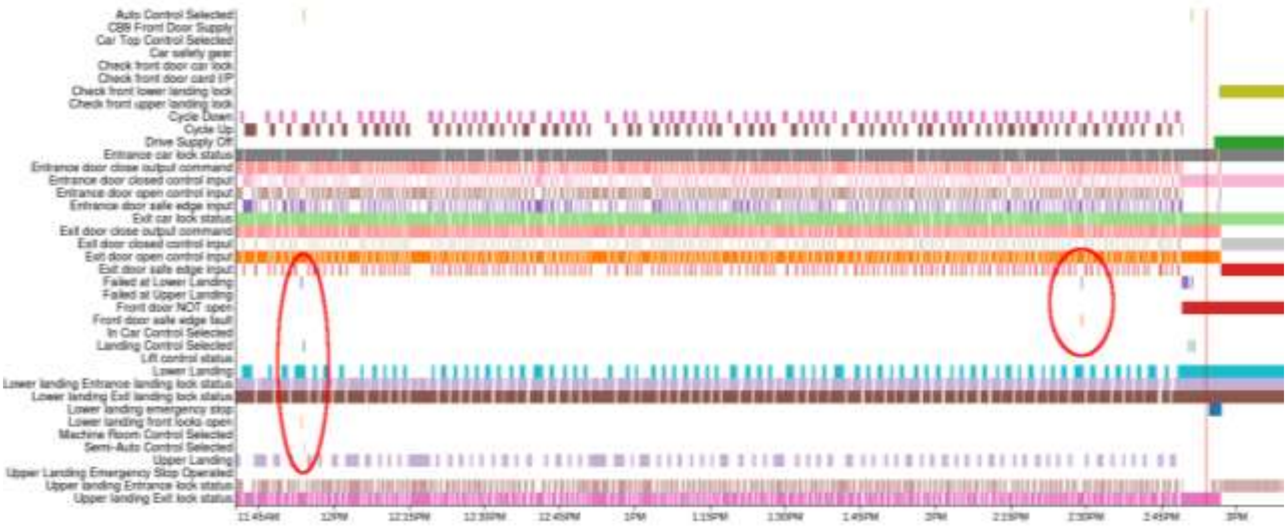


Figure 6 Example of a door fault, 3rd May 2018, Lift 4

5.3 Response times

The occurrence of events that corresponded to actual failures was compared to faults raised by the station staff. It was found that if alerts had been set up, there would have been early warnings for many of the faults which in some cases could have informed maintainers of an issue hours earlier and avoided any loss of passenger service.

The average time saved was around 40 minutes with some faults occurring in the evening and not being picked up until the start of traffic the following morning resulting in disruption during the busy morning peak which could have been avoided. An example of this is shown in Figure 7. The vertical red line indicates a fault being raised to request maintainer attendance, the yellow one is the arrival on site and the green one is the recorded resolution time. The fault was reported four hours after it occurred.

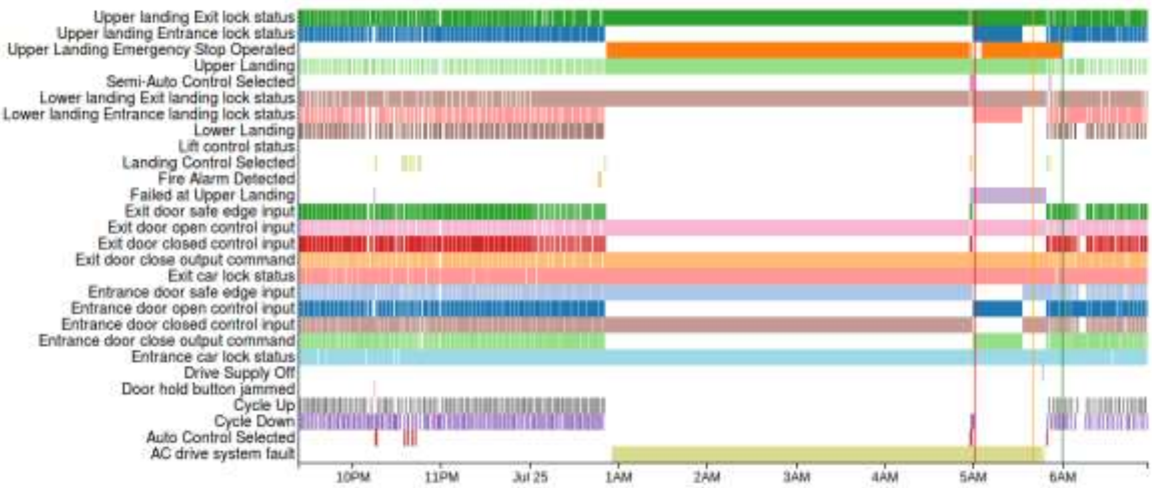


Figure 7 AC drive fault on 25th June 2017, Lift 1

5.4 Unreported faults

It was found from the analysis that there were a few events whereby the lift entered a failed state but was reset locally and no fault was raised by the station staff. In these instances, the maintainers were unlikely to be aware that an issue has occurred and there may be a skewed perception of the reliability of the assets.

It should be noted that if there were alerts to be configured, this would increase the workload of the maintenance contractor and could present a risk of 'information overload'. The design of alert notifications and any business logic behind them requires careful consideration to ensure that they are of value.

5.5 Operational issues

On several occasions, it could be seen that the control was switched between landing and auto control repeatedly prior to a fault occurring. An example of this is shown in Figure 8.

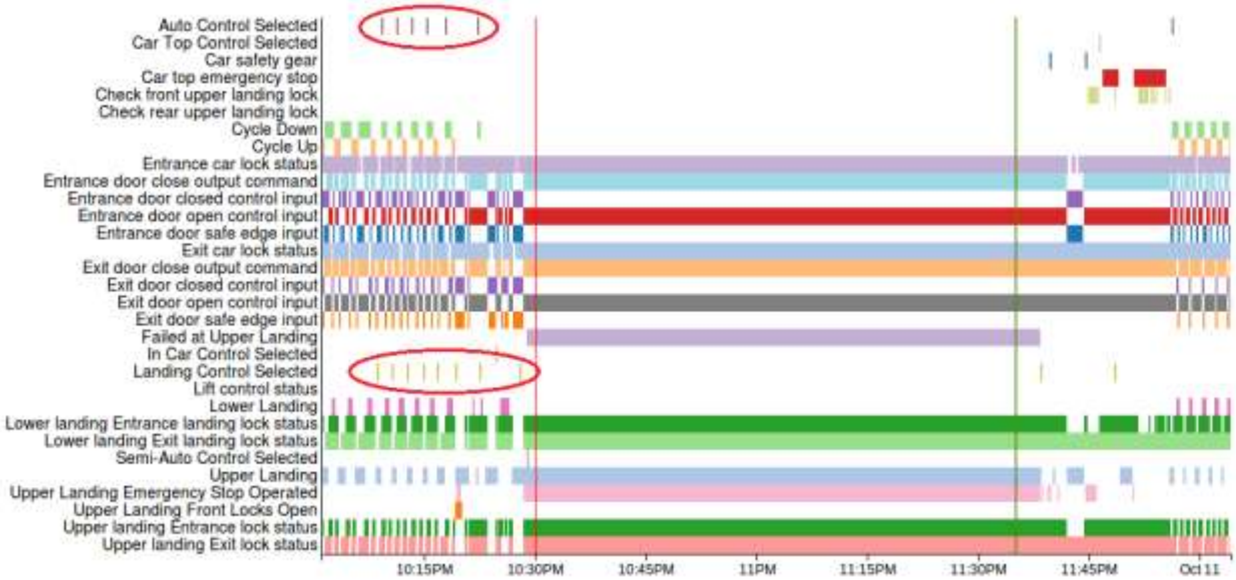


Figure 8 Manual control override prior to fault occurring, 11th October 2017, Lift 4

Enquiries were made with the station staff who reported that they do sometimes manually change over the control mode when footfall is high to keep the lifts moving as quickly as possible. It appears that in some cases this is causing the lift to overshoot the landing and a request has been made to avoid this practice. The historical data can be used to identify when such events are happening to feed back to the station staff, and a more effective solution of modifying the controller program is now being explored.

5.6 Precursors to failures and predictive analytics

The data was analysed to determine if it was possible to spot any developing faults or precursors to failures. After profiling the normal asset behaviour during periods with no known issues, this was compared with the activity during service disruption. Anomalies could be clearly seen where the normal duty cycle of the lift was interrupted, accompanied by the activation of alarms or fault sensors.

Further analysis was undertaken from times of known faults to look for the identified anomalous sensors. It was found that some lifts experienced intermittent faults hours and sometimes days in advance of a service disrupting fault. Disseminating between intermittent faults and actual precursors to a failure proved to be a challenge.

Alternative methods for anomaly detection were then considered. A common way to identify anomalies in machine behaviour is to use control charts in continuous readings. In this case, measurements of entry and exit doors closing times were used. The time series appeared to be stable and did not show any significant change prior to a fault.

Investigation into automatic extraction of event sequences was considered, made possible due to the cyclic behaviour of the lift system. If a standard sequence could be extracted, this could be profiled to make it easier to track for anomalies in the asset state. By taking the differences in time between all binary sensor changes and sorting them, a typical sequence was identified which defined a fingerprint of the asset that could be monitored continuously. This work is essential in preparing the data for further analysis using advanced anomaly detection methods based on machine learning. To do this effectively would require a larger dataset and this is an area requiring further work.

6 DISCUSSION

The examples presented show some of the insights gained from the use of in-depth remote lift monitoring. The new information can be leveraged to improve lift operation and maintenance, which could lead to increased reliability and reduction of downtime. The challenge in practice is to turn the information into actionable intelligence.

Remote monitoring is a powerful tool. To deliver real benefits it must be used regularly, for example as part of regular technical review meetings, and may require some training. Having immediate access to historical data enables retrospective analysis to be done objectively. The knowledge, not only of the occurrence of an incident, but also the events that led up to it and the outputs of internal diagnostics, aids the failure analysis process. Reviewing the monitoring information manually, at least in the early stages, is helpful in identifying anomalous behaviour and addressing any recurring issues as well as providing a record of maintenance performance levels. Additionally, the preventative maintenance activities should be reviewed and adjusted based on asset utilisation and dominating failure modes.

The integration of remote asset monitoring in existing organisational processes is necessary to achieve the reduction in downtime and cost savings they can offer. The early detection of faults cannot shorten the response time on its own, and must generate an appropriate notification to be sent to the asset maintainer. Additionally, the maintenance process and contract must accommodate for the use of this information. Often, the validity of automated alerts is challenged, and in these cases, there must be steps to efficiently verify the alerts and raise a manually confirmed fault as well as feeding back improvements to the business logic. Providing access to the monitoring system for station staff is an effective way to increase their awareness. Even when done informally, this promotes transparency within the organisation and spreads knowledge.

The benefits of this system can also extend to the customer, for example, providing status information from the asset could improve the communication of lift availability to the public, allowing them to plan their journey based on up to the minute data. This would raise the organisational profile and improve the customer experience, particularly for mobility-impaired customers, and is this is now being explored.

7 CONCLUSIONS

The findings from this trial have demonstrated that there are benefits in capturing in-depth data from lift programmable logic controllers for improved fault response, diagnostics and a better understanding of asset operation and condition. This can add value not only to the maintainer but also to asset managers, operational staff and lift users and has been achieved with minimal investment and in a way that provides flexibility in how the data is used. The system presented can be adapted for use on other types of controller including microprocessor-based controllers, although in future, it would be advantageous for access to data from controllers to be considered when scoping new installations and refurbishments.

Improving reliability and asset performance on infrastructure networks is an ongoing process, during which understanding and capability are built over months and years relying on effective documentation of findings from investigations for continuous improvement. Having a detailed view of asset behaviour is clearly advantageous, and if used alongside other sources of data this can be a valuable tool to support a data-driven maintenance regime. However, effective configuration of the business logic to translate data into actionable insights, a suitable user interface and having the necessary people and processes in place are all essential to achieving the benefits.

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BIOGRAPHICAL DETAILS

Ben Langham is an Asset Condition Engineer at London Underground, where he has held various roles in lift and escalator maintenance over the last ten years since completing the Metronet Rail engineering graduate scheme. Ben has led a number of initiatives using technology and data to enable proactive, data-driven maintenance and inform strategic planning. He has a BEng in Mechanical Engineering from the University of Reading, an MSc in Advanced Engineering Design from Brunel University and is a Chartered Engineer with the Institution of Mechanical Engineers.

Vergil Yotov is a system engineer and data analyst with Amey Consulting since 2016. He spent two years working for London Underground designing and implementing innovative ways for remote condition monitoring and performance optimisation. He has a BSc in Astrophysics from the University of Edinburgh and an MSc in Computer Science from the University of Birmingham.

A Systematic Methodology for Analysing Zoning Options for a Building Using Dynamic Programming

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Keywords: lift traffic design, zoning, handling capacity, uppeak traffic.

Abstract. In the designing phase of a building, the number of lifts, their capacities and nominal speeds are selected. In case of high-rise buildings, it is a common practice to divide the building into fixed contiguous floor segments called zones to save core area taken by lifts. Typically, each zone is served by a group of lifts, and zones do not have common floors except the entrance floor. The zoning design aims at similar service quantity and quality among all zones. Each lift group should satisfy the traditional design criteria related to handling capacity, interval, and nominal travel time. Finding a good zoning solution is not an easy task since, in general, the number of different zonings increases exponentially as a function of the number of served floors. Current practice in the lift industry is more or less based on rules of thumb, duty table calculations, and the designer's expertise. This paper introduces a dynamic programming program for finding an optimal solution for the static zoning problem. It assumes the uppeak traffic condition. The developed method is an extension of Powell's work carried out almost 50 years ago. The solution to the optimization problem divides the upper floors of the building into fixed disjoint zones and, for each zone, specifies the number of lifts as well as their sizes and rated speeds. Optimal zonings with respect to uppeak filling time, core area occupied by all lifts in all floors, and the total number of lifts over all zones objectives are analysed for a large set of hypothetical office buildings. The results show in general how many zones and lifts per zone are needed, what is the impact of different objective functions on optimal zones and how much zoning decreases core area occupied by the lifts.

1 INTRODUCTION

In a building having up to 15-20 floors there is usually a single lift group serving every floor. As the building height increases, lift groups serving all floors occupy a bigger proportion of the building core area to satisfy lift traffic design criteria. In order to save core area, floors can be divided into contiguous floor segments called zones, and each zone is served by a separate lift group. Zoning reduces passengers' transit times in lifts and times to destination due to fewer number of intermediate stops between passengers' origin and destination floors.

In a typical case, a building requiring a large lift group is split into two zones, the low- and the high-rise. The low-rise lifts serve floors immediately above the entrance while the high-rise lifts express past the low-rise floors and serve only the top part of the building. Thus, about half of lift entrances are saved. Furthermore, the low-rise lifts can be designed with smaller rated speed than the high-rise lifts since the total travel is shorter. This allows smaller machineries, which are less expensive and consume less energy. In this manner, the building can be divided into as many zones as needed. Practical limit is about 4-5 zones. If lifts occupy too large area on the ground level, lift groups can be stacked on top of each other. Shuttle lifts transport passengers from the ground floor to a sky lobby from which local lift groups pick them up to their final destinations [1].

Core area can also be reduced by special lift solutions such as double-deck lifts, two independent lift cars in one shaft or multi-car systems [2-6]. In these systems, more than one lift car is placed in one shaft, which increases lift handling capacity per shaft. With double-deck lifts, the number of lifts shafts can be reduced by 30-40% and with multicar systems even more. In tall buildings, more than 50% of core area can be saved by sky lobby arrangements together with double-deck lifts [7]. Lift group control such as the destination control system (DCS) can decrease the number of stops per round trip too, enabling higher handling capacity - especially in uppeak traffic [8,9]. DCS has a wider upper bound to the number of lifts and served floors in a lift group. Firstly, the DCS reserves enough time for passengers to walk to their assigned lifts, which ensures efficient passenger transfer times. Secondly, the DCS reduces the number of stops per round trip, which is similar to the effect of zoning with the conventional control system.

In the selection of a zoning arrangement, the core area occupied by lifts is not the only thing to be considered. Building filling time should also be taken into consideration, which is expressed by a criterion for relative lift handling capacity [10,11]. Average passenger waiting time or lift departure interval from the main lobby should have a target or an upper limit for a good service quality. In addition, the selection of lift rated speed should satisfy nominal travel time criterion. Rated speed should not be too high so that lifts rarely reach the full rated speed and thus become unnecessarily expensive. Neither should it be too low since it decreases lift group handling capacity. Lift banks are preferably symmetric with equal car capacities, and often with an even number of shafts. Other possible design considerations are lift energy consumption, passenger journey times, evacuation time, round trip time or whatever is considered important in the building under consideration [13].

This paper focuses on the static zoning of a building without neither sky-lobbies nor any special lift solutions. Finding a good zoning arrangement is not an easy task since, in general, the number of different zoning grows exponentially as a function of the number of the served floors. For example, the number of different zonings for a building having 60 floors above entrance level is about 10^{18}, meaning that a simple enumeration method cannot be utilized. Therefore, more clever approaches are needed.

According to our knowledge, the first optimization method for zoning was introduced almost 50 years ago by Powell [10,11]. The method is based on a dynamic programming. It is capable of finding an optimal solution within seconds. The method did not, however, receive much interest from the lift industry. The current practice in zoning is more or less based on rules of thumb, duty table calculations, and the designer’s expertise. This may mean that the best zoning is not found.

In this paper, the Powell’s method is modified such that: i) the rated speed is selected based on the highest floor of a zone instead of the lowest floor; ii) the car load factor is a decision variable instead of being a constant fixed to 100 % (or to any other constant value) since using fixed car load factors may lead to over- or under-sizing; iii) the number of lifts in a zone should be at minimum and it can differ from values of other zones only by 2 but do not need to be even; and iv) round trip time formula presented in [14] is used which takes into account the exact running times of each flight during the round trip, instead of using flight time approximations.

The solution to the dynamic programming program divides the upper floors of the building into contiguous disjoint zones and, for each zone, specifies the number of lifts as well as their sizes and rated speeds. The traffic is assumed to be uppeak traffic [15], and group controller the conventional full-collective control - for which uppeak calculation is sufficient to guarantee proper lift service in all traffic situations. Optimal zonings with respect to uppeak filling time, core area occupied by all lifts in all floors, and the total number of lifts over all zones are analysed for a large set of hypothetical office buildings in order to see in general how many zones and lifts per zone are needed, what is the impact of different objective functions on optimal zones and how much zoning decreases core area occupied by the lifts.

2 BASICS OF ZONING

2.1 Two zones in an office building

In order to demonstrate the basic principles of zoning, an office building with 14 populated upper floors above entrance level is split into two zones. It is worth noticing that typically buildings with 15 or more floors require zoning [6]. For simplicity, the building has equal floor-to-floor distances of 3.3 m and a population of 145 persons on each upper floor. Typical design criteria applied are: uppeak handling capacity ($\%HC5$) of 12% of population per 5 minutes and up-peak interval ($UPPINT$) of 30 seconds. Three different zoning arrangements are considered. Table 1 shows uppeak calculation results as well as the parameters for each lift group under consideration: the number of lifts, L; rated speed, v; rated passenger capacity, CC, i.e., the maximum number of passengers that a lift car can accommodate; average number of passengers, P, in the car at departure from the main entrance floor, which is assumed to be $0.8 \times CC$. Parameter UPPINT@12% shows the interval during up-peak traffic when the traffic intensity is 12 % of the total population within 5 minutes. Other common parameters used for each lift group are acceleration 1.0 m/s^2, jerk 1.6 m/s^3, door closing time 3.1 s, door closing delay time 0.9 s, door opening time 1.4 s, door pre-opening time 0 s, start delay 0.7 s and passenger transfer time 1.0 s to enter or leave the car.

Table 1 Parameters and uppeak calculation results for simple zoning

Group	L	v	CC	P	$\%HC5$	$UPPINT$	$UPPINT@12\%$
Non-zoned	8	3.0	17	13.6	10.7%	18.8 s	N/A
Non-zoned – large cars	8	3.0	24	19.2	12.7%	22.4 s	21.3 s
Low-rise	4	1.6	17	13.6	14.0%	28.7 s	25.8 s
High-rise	4	3.0	17	13.6	12.9%	31.2 s	30.0 s

This lift group design assumes rated passenger capacity of 17 persons. The group of eight such cars does not reach the relative handling capacity criterion of 12%. The eight-car group can be split into two four-car groups that satisfy the design criteria. In addition to the main entrance (ground) floor, the Low-rise serves floors 1…7 and the High-rise floors 8…14. The rated speeds of low-rise lifts can be reduced to 1.6 m/s due to the shorter total travel. Another way to satisfy the criterion is to increase the car size to 24 person, but it requires more core area than the zoned solution does and that size lift cars are very rare in office buildings.

The performance graph shown in Figure 1 demonstrates the above lift traffic design with 17-person cars. The graph depicts interval as a function of handling capacity for car load factors (CLF) from 10% to 80%. Thus, each point corresponds to $UPPINT$ and $\%HC5$ calculated with $P_{CLF} = CLF \times PC/100\%$ passengers, e.g., $P_{10} = 1.7$. Interval at the given handling capacity criterion, i.e., $UPPINT@12\%$, should be used to decide whether service quality satisfies the requirement instead of the maximum $UPPINT$ with 80% CLF. Such a point can be deduced from the graph as the intersection of a particular plot with the 12% vertical line. For example, the Low-rise and the High-rise intersect 12% handling capacity with $P_{62} = 10.5$ persons and $P_{72} = 12.2$ persons, respectively.

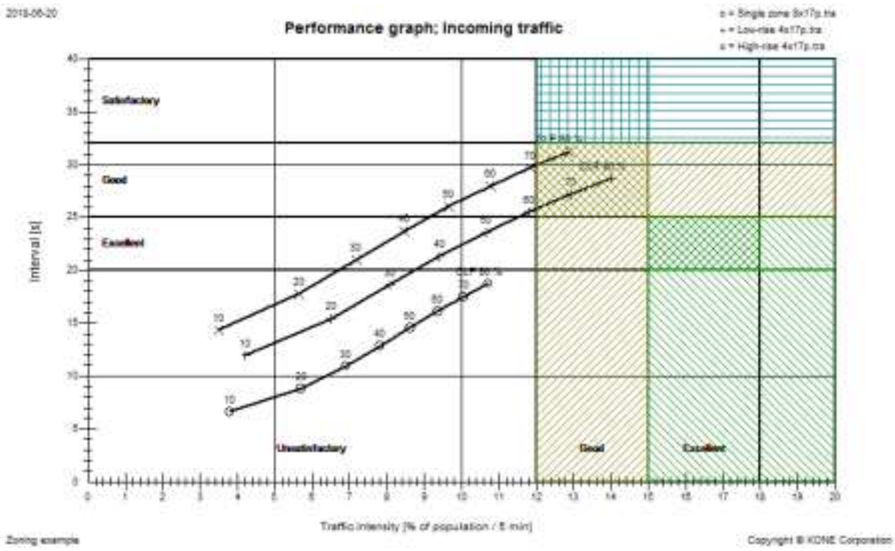

Figure 1 Uppeak interval with respect to traffic intensity with increasing CLF values

The performance graph can be used to guide the lift design process. A curve crossing through the shaded area represents an acceptable lift group design although the performance can be compared to the detailed design criteria. Since the zoning design aims at harmonized service quality between the rises, the curves of different rises should become as close to each other as possible. In this case, the Low- and the High-rise are rather unbalanced. The Low-rise has about 10% more handling capacity and about 15% shorter interval compared to the High-rise. As shown by this example, the express zone of the High-rise adds a constant time to round trip time, which easily makes interval longer than the criterion. The express zone can be compensated by increasing rated speed. In this case, notable improvements can be observed up to speeds of 3.5 or 4.0 m/s.

2.2 Impact of a transfer floor on zoning

A transfer floor is an upper floor, which is common to two or more lift groups. The transfer floor allows fluent interfloor traffic between the zones as passengers do not need to travel via the main entrance floor. During morning uppeak passengers, however, soon learn to use the fastest route to the transfer floor. Usually, the fastest route is with the higher group, for which the transfer floor is the first stop after the express zone. Therefore, lift traffic design should assume that the transfer floor population is served by the higher group to avoid under-capacity for that lift group.

The above example of an office building is continued by considering a transfer floor between the Low-rise and the High-rise on level 7. It is assumed that passengers can use both groups to reach level 7. Figure 2 shows performance graphs of the High-rise in the cases that 0%, 50% or 100% of level 7 population use it during morning uppeak. Clearly, level 7 population invalidates the original traffic design for the High-rise as both handling capacity and interval do not anymore satisfy the design criteria. This situation can be avoided in practice by, e.g., locking car calls to the transfer floor from the High-rise when lifts are on the main entrance floor [7].

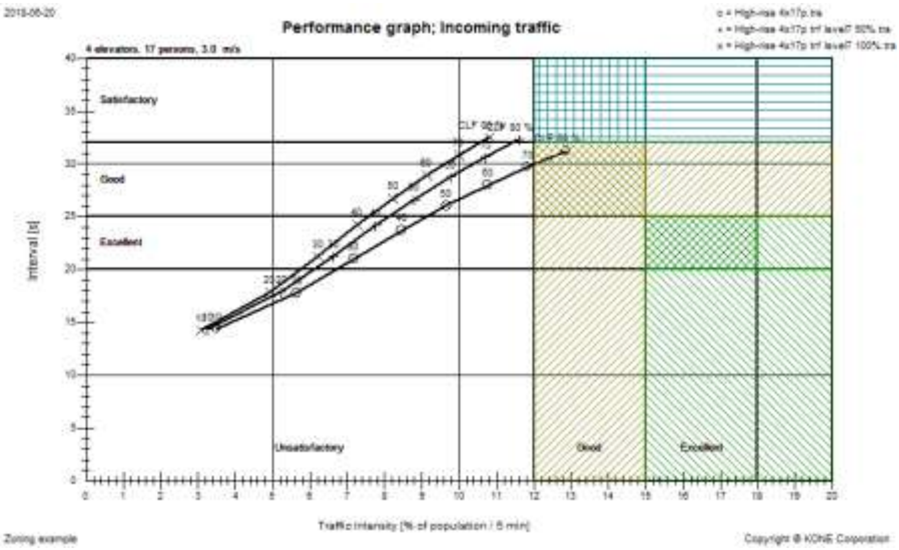

Figure 2 Different usage scenarios for the High-rise transfer floor 7

3 ZONING ALGORITHM

This section introduces a dynamic programming procedure to find an optimal zoning for a building.

3.1 Problem description and notation

Consider a general high-rise building containing N populated floors, indexed as $1 \ldots N$. Level 0 is the only entrance floor. The following constraints are assumed to hold for each zone:

(C1) Rated lift speed is subject to the nominal travel time (NTT) requirement, that is, time period for a lift to travel from the ground floor to the highest floor in the zone without any stops must be shorter than a predetermined value.

(C2) Relative handling capacity ($\%HC5$) must meet or exceed a predetermined value.

(C3) Interval ($UPPINT$) must be shorter than a predetermined value.

(C4) The number of lifts must be as small as possible.

(C5) The number of lifts in must be between n and $n+2$.

(C6) The lift groups do not have common floors except the entrance level.

(C7) Rated passenger capacity, CC, of a lift is the same for all lifts.

Uppeak round trip time (RTT) of a lift begins when lift's doors start to open at the entrance level and ends when the doors again start to open at the entrance level after making a full trip up and down. During the round trip, the lift transports P passengers on average from the main entrance floor to their destination floors. The value of P may vary from one passenger to 80% of rated passenger capacity according to the traditional definition of handling capacity [12]. The RTT calculation used in this paper takes into account the exact running times of each flight during the round trip [14,15]. Let $RTT(i,k,v,P)$ denote the round trip time of a lift when it serves populated floors from i to k, its rated speed is v and the average number of passengers in the car is P at departure from the entrance floor.

Without constraint (C5), a building consisting of N populated floors can theoretically have Z combinations of different zoning arrangements,

$$Z = 2^{N-1}. \quad (1)$$

If the number of zones is restricted to m, then Z becomes

$$Z = \sum_{k=1}^{m} \binom{N-1}{k-1}, \tag{2}$$

where $\binom{N-1}{k-1} = \frac{(N-1)!}{(k-1)!*(N-k)!}$, and $n! = n*(n-1)*...*2*1$. If the number of lifts in each zone can differ at most by a certain value, that is, (C5) must hold, then there may not be a general formula for Z since it is now dependent on the building population distribution.

3.2 Dynamic programming algorithm

Three different zoning policies are considered: maximum filling time (FT), lift core area occupied on all floors (CA), and the total number of lifts in all zones (LL). Optimal zoning with respect to maximum filling time was first considered by Powell [10,11]. Denote by $M_Z^f(k)$ the objective value associated with objective function f when floors 1,2 ... k are served by Z zones, $Z \leq m$. Furthermore, let the objective functions are defined as follows

$$FT(i,k,v,P,L) = \frac{POP(i,k)}{P} \times \frac{RTT(i,k,v,P)}{L}, \tag{3}$$

$$CA(i,k,v,P,L) = (k+1) \times L \times A(CC), \tag{4}$$

$$LL(i,k,v,P,L) = L, \tag{5}$$

where L lifts serve levels i to k with total population $POP(i,k)$, and $A(CC)$ denotes the standard shaft dimensions of a lift with rated load greater than or equal to $CC \times 75\ kg$ [16].

The general idea of the algorithm is to iteratively split the building into m zones and then select the solution which minimize the objective value. Briefly, in the first step, the optimal 1-zone arrangement is defined when floors 1 to k are served. This is repeated for each $k = 1, \ldots, N$. Then, in the second step, the optimal 2-zone arrangement is generated by choosing the optimal splitting point x such that first zone serves floors $1, \ldots, x-1$, and the second zone floors $x, \ldots, k$. The optimal 1-zone arrangements read from the first step. This step is repeated for each $k = 2, \ldots, N$. Then, in the third step, the optimal 3-zone arrangement is found by selecting the optimal splitting point x such that third zone serves floors $x, \ldots, k$, and zones 1 and 2 serve floors $1, \ldots, x-1$. This step is repeated for each $k = 3, \ldots, N$. Notice that the optimal 2-zone arrangement is already generated in the second step. The method continues until the m-zone arrangement is generated. If at any step a zoning does not satisfy constraint (C5), it is considered as infeasible and the objective value of such a solution is set to infimum. After the last step, the optimal solution is selected.

Formally, the optimal zoning $M^f(N)$ with respect to objective function f for a building having N upper floors is obtained by the following dynamic programming recursion

$$M^f(N) = \min_{2 \leq n \leq 10} \left\{ \min_{1 \leq Z \leq m} \left[\min_{Z \leq x \leq N} F\left(M_{Z-1}^f(x-1), f(x,N,v^*,P^*,L^*)\right) \right] \right\}, \tag{6}$$

where v^* satisfy (C1), and P^* as well as L^* are selected so that constraints (C2)-(C5) are satisfied. The lower bound of P is one passenger and the upper bound $0.8 \times CC$. The aim of the first policy is to find a zoning arrangement where the filling times of all zones are as nearly equal as possible and as small as possible. This is achieved by minimizing the maximum filling time. Hence, F corresponds to the maximum of M_{Z-1}^f and f. The other policies, i.e., the minimum core area and minimum number of lifts, are additive in nature and, therefore, function F is a summation for them.

4 OPTIMAL ZONING SOLUTIONS FOR OFFICE BUILDINGS

This section provides the computational results for a large set of office buildings, which is obtained by varying the number of populated floors between 1 and 60, and varying the number of persons per floor from 5 to 200 in steps of five. Table 2 gives lift and building parameters that are used in all cases and Table 3 shows feasible lift kinematic parameters.

Table 2 Common lift and building parameters

Door opening time [s]	1.4	Start delay [s]	0.7
Door closing time [s]	3.1	Passenger transfer time [s]	1.0
Door closing delay time [s]	0.9	Rated passenger capacity [persons]	21
Door pre-opening time [s]	0.0	Floor-to-floor distance [m]	3.3
Shaft area [m^2]	6.75		

Table 3 Feasible rated speeds as well as the used accelerations and jerks for each speed

Speed [m/s]	1.0	1.6	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0
Acceleration [m/s^2]	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Jerk [m/s^3]	1.2	1.2	1.2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6

The maximum number of zones is set to 20. The number of zones in tall buildings is in practice limited to 4 or 5, therefore 20 is too large. The upper bound for the zones is however kept in 20 in order to see what is the optimal number of zones. The lift group design criteria for each zone are: handling capacity of 12% of population per five minutes, interval of 30 seconds, and nominal travel time of 25 seconds. Nominal travel time is defined in constraint (C1).

4.1 Optimal number of zones

Figure 3 displays the optimal number of zones when the core area (left), the total number of lifts (centre), and the maximum filling time is minimized (right). As an example, for a 40-storey building with 100 persons per floor, the optimal number of zones are 4, 3, and 20 with respect to the core area, total number of lifts, and the maximum filling time, respectively. The colours in the figure represent the values in the cells, green being small number of zones, then turning to yellow and red as the number of zones increases.

Objective function / Number of persons per floor

Core Area

Floor	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	2	2	3	3	3	3	4	4	4	5	5	6	6	7	7	7	8	8	9	10
58	2	2	2	2	3	3	3	4	4	5	5	5	6	6	7	6	8	8	9	9
56	3	2	2	2	3	3	3	4	4	5	5	6	5	6	6	6	7	8	9	9
54	3	2	3	3	3	3	3	4	4	4	5	5	5	6	6	6	7	7	8	9
52	2	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7	8	8
50	2	2	2	2	3	3	3	3	4	4	5	5	5	5	6	6	7	7	8	9
48	2	2	3	2	2	3	3	3	4	4	5	5	5	5	6	6	6	7	7	8
46	2	2	2	2	2	3	3	4	4	4	4	5	4	5	5	6	6	6	7	8
44	2	2	2	3	2	2	3	3	4	4	4	5	4	5	5	6	6	6	7	8
42	1	2	3	2	3	3	3	3	4	4	4	4	4	5	5	5	6	6	6	7
40	2	3	2	3	3	2	2	3	3	4	4	4	4	4	5	5	5	6	6	7
38	2	2	2	2	3	2	3	3	3	3	4	4	4	4	4	5	5	5	6	7
36	2	2	2	2	2	2	2	3	3	3	3	4	3	4	4	5	5	5	5	6
34	2	1	2	3	3	2	3	2	3	3	3	4	3	4	4	4	5	6	5	6
32	2	2	2	2	2	2	2	3	3	3	3	3	3	5	4	4	5	5	5	6
30	2	2	3	2	2	3	3	2	3	3	3	3	3	3	4	5	5	4	5	5
28	1	2	3	2	2	2	2	3	3	3	3	3	4	4	3	4	5	5	4	5
26	1	2	2	2	2	3	2	2	3	2	3	3	3	3	3	4	3	4	4	5
24	1	1	2	3	2	2	2	2	2	2	2	3	3	4	4	4	3	4	4	4
22	1	2	2	2	2	2	2	2	2	3	2	3	2	3	3	3	3	3	3	4
20	2	2	2	1	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4
18	2	2	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3
16	1	1	2	2	2	1	3	2	3	2	2	2	3	3	3	3	3	3	3	3
14	1	1	2	1	2	2	2	2	2	2	2	2	3	2	2	3	3	3	2	2
12	1	1	2	2	1	2	2	1	2	2	1	1	3	2	2	2	2	2	2	2
10	1	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
8	1	1	2	1	1	1	2	2	2	2	2	1	2	2	2	2	2	2	2	2
6	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1	2
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Total number of lifts

Floor	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	1	1	1	2	2	3	3	3	4	4	4	5	5	6	6	7	7	7	8	8
58	1	1	1	2	2	3	3	3	3	4	4	5	5	6	6	6	7	7	8	8
56	1	1	1	2	2	2	3	3	3	4	4	5	5	6	6	6	7	7	7	8
54	1	1	1	1	2	2	3	3	3	4	4	4	5	5	6	6	6	7	7	8
52	1	1	1	1	2	2	2	3	3	4	4	5	5	5	5	6	6	6	7	7
50	1	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7
48	1	1	1	1	2	2	2	3	3	3	3	4	4	5	5	5	6	6	6	7
46	1	1	1	1	2	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6
44	1	1	1	1	1	2	2	2	2	3	3	4	4	4	5	5	5	5	6	6
42	1	1	1	1	1	2	2	2	2	3	3	4	4	4	4	5	5	5	6	6
40	1	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	5	5	5	6
38	1	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4	5	5	5
36	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4	4	4	4	5	5
34	1	1	1	1	1	2	1	2	2	2	3	3	3	3	3	4	4	4	4	5
32	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4	5
30	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4	4	4	4
28	1	1	1	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4
26	1	1	1	1	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4
24	1	1	1	1	1	1	1	1	1	2	2	2	2	2	3	2	3	3	3	4
22	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3
20	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3
18	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	3
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Maxium filling time

Floor	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	20	20	20	20	19	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
58	20	20	20	20	19	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
56	20	20	20	20	20	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
54	20	20	20	20	20	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
52	20	20	20	20	20	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
50	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
48	20	20	20	20	19	20	19	20	20	20	20	20	20	20	20	19	20	19	20	20
46	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	19	20	20	20
44	20	20	20	20	20	20	20	20	19	20	20	20	20	20	20	19	19	19	20	19
42	20	20	20	19	19	20	20	19	19	20	20	20	20	19	19	20	20	20	19	20
40	20	20	20	18	18	20	20	19	20	20	20	20	20	19	19	20	20	20	20	20
38	19	19	19	17	17	20	20	20	20	20	20	20	20	19	19	20	20	20	19	19
36	18	18	18	16	16	20	20	20	20	19	20	20	20	19	20	20	20	20	20	20
34	17	17	17	15	15	20	20	20	20	19	20	19	20	19	19	20	20	20	20	20
32	16	16	16	14	14	20	20	20	20	20	20	19	20	19	19	20	20	20	19	19
30	15	15	15	13	13	20	20	20	20	20	20	20	20	19	19	20	20	20	19	19
28	14	14	14	12	12	20	20	20	20	20	20	20	20	19	19	20	20	20	17	17
26	13	13	13	11	11	20	20	20	20	20	20	20	20	19	17	20	20	18	15	15
24	12	12	12	10	10	18	20	20	20	20	20	20	20	17	15	20	20	16	13	13
22	11	11	11	9	9	16	18	19	19	19	19	19	19	15	13	18	18	14	11	11
20	10	10	10	8	8	14	16	17	17	17	17	17	17	15	13	16	16	12	9	9
18	9	9	9	7	7	13	14	15	15	15	15	15	15	13	11	14	14	12	9	9
16	8	8	8	6	6	11	12	13	13	13	13	13	13	13	11	12	12	10	7	7
14	8	8	8	6	6	10	11	11	11	11	11	11	11	11	9	10	10	8	7	7
12	7	7	7	5	5	9	9	9	9	9	9	9	9	9	9	8	8	8	7	7
10	7	7	7	4	4	7	7	7	7	7	7	7	7	7	7	6	6	6	5	5
8	5	5	5	4	3	6	6	6	6	5	5	5	5	5	5	4	4	4	4	4
6	4	4	4	4	4	3	3	4	4	4	4	4	4	4	4	3	3	3	3	3
4	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 3 The optimal number of zones when the core area is minimized (left), the total number of lifts is minimized (centre), and the maximum filling time is minimized (right).

In general, the optimal number of zones increases as a function of populated floors as well as the number of persons per floor. However, when minimizing the filling time, the optimal number of zones is strongly related to the number of upper floors. The number of floors per zone is very small, typically between one and three. Such a static zoning is impractical. The results above indicate that filling time objective contradicts with both the core area and the total number of lifts objective. Thus, the zoning should be considered as a multi-objective optimization problem, where the filling time objective puts weight on solutions that have as equal filling time and handling capacity as possible and either the core area or the number of lifts objective prefers solutions with the minimal number of shafts.

4.2 Maximum number of lifts over all zones

Figure 4 shows the maximum number of lifts over all zones when the core are is minimized (left), the total number of lifts is minimized (centre), and the maximum filling time is minimized (right). The figure reveals that for the core area and the maximum filling time objectives, the optimal number of lifts over all cases considered is always less than or equal to 8. This value corresponds to the maximum practical number of lifts that has been used in case of conventional control. For the total number of lifts objective, the maximum number of lifts goes up to 14, which is not common in the lift industry but is a possible with destination control.

Floor	Objective function / Number of persons per floor: Core Area																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	4	6	6	7	7	7	7	7	8	7	7	6	7	6	6	7	6	6	6	6
58	4	6	7	8	7	7	7	7	7	7	7	7	6	7	6	8	6	6	6	6
56	4	6	7	8	7	7	8	7	7	7	6	6	7	6	7	7	7	6	6	6
54	4	5	5	6	7	7	7	7	7	7	6	7	7	7	7	7	6	6	6	5
52	4	5	6	7	7	7	7	7	7	7	6	6	6	6	6	7	6	6	6	6
50	4	5	6	7	6	7	7	7	7	7	6	6	6	7	6	7	6	6	6	5
48	4	5	5	7	7	7	7	7	6	6	6	6	6	6	6	6	7	6	6	5
46	4	5	6	7	7	6	7	6	6	7	7	6	7	6	7	6	6	6	6	5
44	4	5	6	5	7	7	7	7	6	6	6	6	7	7	6	6	6	6	6	5
42	4	5	5	6	6	6	7	7	6	6	6	6	6	6	6	6	6	6	6	5
40	3	4	5	5	5	7	7	7	7	6	6	6	6	6	6	6	7	6	6	5
38	3	4	5	6	5	7	6	6	6	7	6	6	6	6	7	6	6	6	6	5
36	3	4	5	6	6	7	7	6	6	6	6	6	7	6	7	6	6	6	6	5
34	3	5	5	5	5	6	6	7	6	7	6	6	7	6	6	6	6	5	6	5
32	3	4	5	5	6	6	7	6	6	6	6	6	6	5	6	6	5	5	6	5
30	3	4	4	5	6	5	5	7	5	6	6	6	6	6	6	5	5	6	5	5
28	3	4	4	5	5	6	6	5	5	6	6	6	5	5	7	6	5	5	6	5
26	3	4	4	5	5	5	6	6	5	6	5	6	6	6	6	5	7	6	6	5
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14	2	3	3	4	4	4	4	4	5	5	5	5	4	5	5	4	4	4	5	5
12	2	3	3	3	4	4	4	5	4	4	6	6	4	5	5	5	5	5	5	5
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8	2	2	2	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4
6	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	3
4	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3
2	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Floor	Total number of lifts																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	6	9	12	8	9	7	8	9	7	8	9	7	8	7	7	6	7	7	6	7
58	6	8	12	7	8	7	7	8	9	7	9	7	7	7	7	8	6	7	6	6
56	6	8	11	7	8	10	7	8	9	7	8	7	7	6	6	7	7	6	7	6
54	5	8	11	14	8	9	7	8	9	7	7	8	7	7	6	6	8	6	6	6
52	5	8	10	13	8	9	10	7	8	7	7	6	6	7	7	6	7	7	6	7
50	5	7	10	13	8	8	10	7	8	9	7	7	8	7	7	7	6	7	8	6
48	5	7	9	12	7	8	9	7	7	8	9	7	7	6	7	7	7	6	6	6
46	5	7	9	11	7	8	9	10	7	8	8	7	7	8	6	6	8	6	6	7
44	5	7	8	11	13	7	8	9	11	7	8	6	7	7	6	6	7	7	6	6
42	4	6	8	10	13	7	8	9	10	7	8	6	6	7	7	6	6	7	6	6
40	4	6	8	10	12	7	7	8	9	7	7	8	9	6	7	7	7	6	6	6
38	4	6	7	9	11	7	7	8	9	6	7	7	8	6	6	7	8	6	6	7
36	4	6	7	9	11	6	7	7	8	6	6	7	7	8	6	6	7	7	6	6
34	4	5	7	8	10	6	13	7	8	9	6	6	7	7	8	6	6	7	7	6
32	4	5	6	8	9	11	12	7	7	8	9	6	6	7	7	6	6	6	6	5
30	4	5	6	7	8	10	12	6	7	7	8	6	6	6	7	7	5	6	6	6
28	3	5	6	7	8	9	11	12	7	7	7	8	9	6	6	6	7	7	6	6
26	3	5	6	7	7	8	10	11	12	6	7	7	8	9	6	6	7	7	7	5
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20	3	4	5	5	6	6	7	8	9	10	6	6	6	6	6	7	7	8	5	5
18	3	4	4	5	6	6	7	7	8	9	9	10	11	6	6	6	6	7	7	5
16	2	3	4	5	5	5	6	6	7	7	8	9	9	10	5	5	5	6	6	6
14	2	3	4	4	5	5	6	6	6	6	7	8	8	9	9	10	5	5	5	5
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6	2	2	2	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	5
4	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3
2	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Floor	Maxium filling time																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
58	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5
56	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5
54	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5
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50	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
48	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
46	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
44	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
42	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4
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34	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4
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20	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	3	3	4	4	4
18	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	3	3	4	4	4
16	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	3	3	4	4	4
14	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	3	3	4	4	4
12	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4
10	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4
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4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
2	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Figure 4 Maximum number of lifts over all zones

4.3 Savings in core area by zoning

The savings in core area as a function of floors is shown in Figure 5 for buildings with 100, 150, and 200 persons per floor. In this case the core area was used as an optimization objective. Saving is calculated with respect to the single zone arrangement. From the figure one can see that it is possible to save core area up to 60 % by zoning the floors in an optimal way in a building with about 60 floors and 150-200 persons per floor.

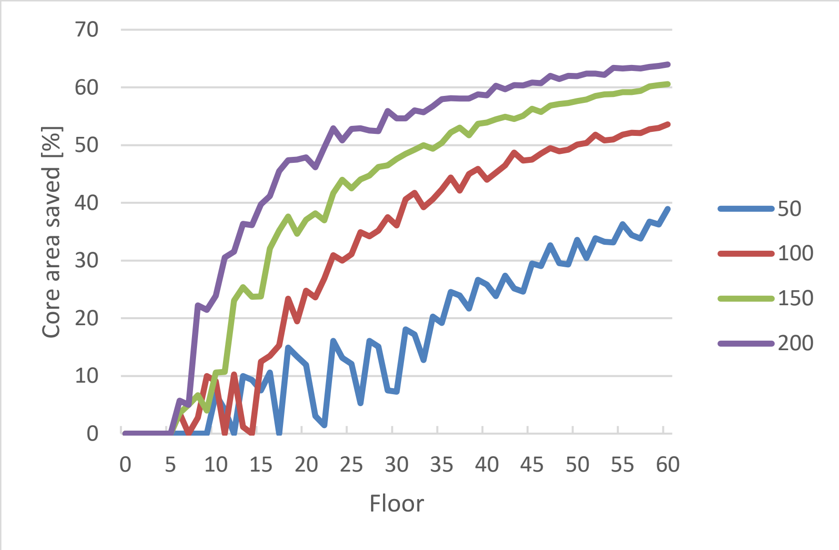

Figure 5 Saving in core area by zoning for buildings containing 50, 100, 150 and 200 persons per floor

4.4 Optimal solutions for a 60-storey office building

The optimal solutions with respect to the core area and the number of lifts are depicted in Figures 6 and 7, respectively, for a building containing 60 floors with the population of 50, 100 and 150 persons per floor. In the figures, each vertical bar represents a lift group and the number above each bar describes how many lifts there are in the group. Light blue colour represents served floors while white colour represents express floors and dark blue the entrance level. The highest floor of the zone is shown on the left and the rated speed on the right. The optimal solution for the filling time objective is not illustrated since the number of zones in all cases is 20.

Objective values for the optimal solutions for each objective are given in Table 4. Values for a single zone solution is reported as well. The number of lifts and core area are close to each other if core area (CA) and number of lifts (LL) is optimized. In a single zone solution and maximum filling time (FT) optimization, the number of lifts and core area can be about twice as big compared to the core area and the total number of lifts optimization when the number of lifts is not restricted.

Table 4 Objective values for different population per floor

Parameter	Population	Single zone	Max *FT*	*CA*	*LL*
Number of lifts	50	20	64	18	17
	100	39	72	30	29
	150	58	79	39	39
Core area [m^2]	50	8235	13811	5029	5380
	100	16058	16693	7452	7803
	150	23881	179993	9416	9794
Filling time [min]	50	40.1	14.9	41.6	40.3
	100	41.2	16.4	41.2	41.7
	150	41.5	19.6	41.5	40.9

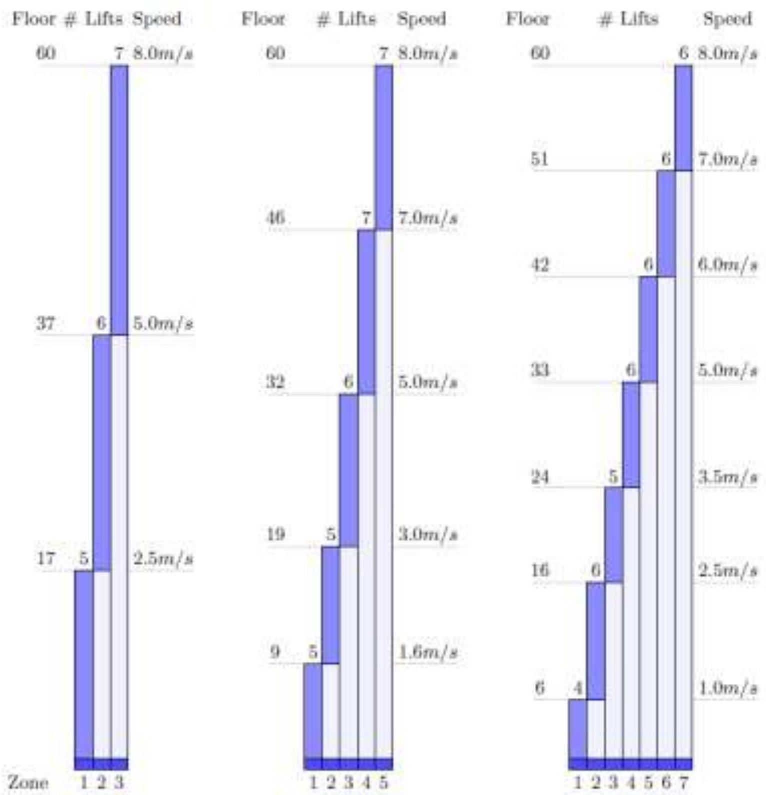

Figure 6 Zoning solutions by optimizing core area for a 60-floor building with 50 (left), 100 (centre), and 150 (right) persons per floor

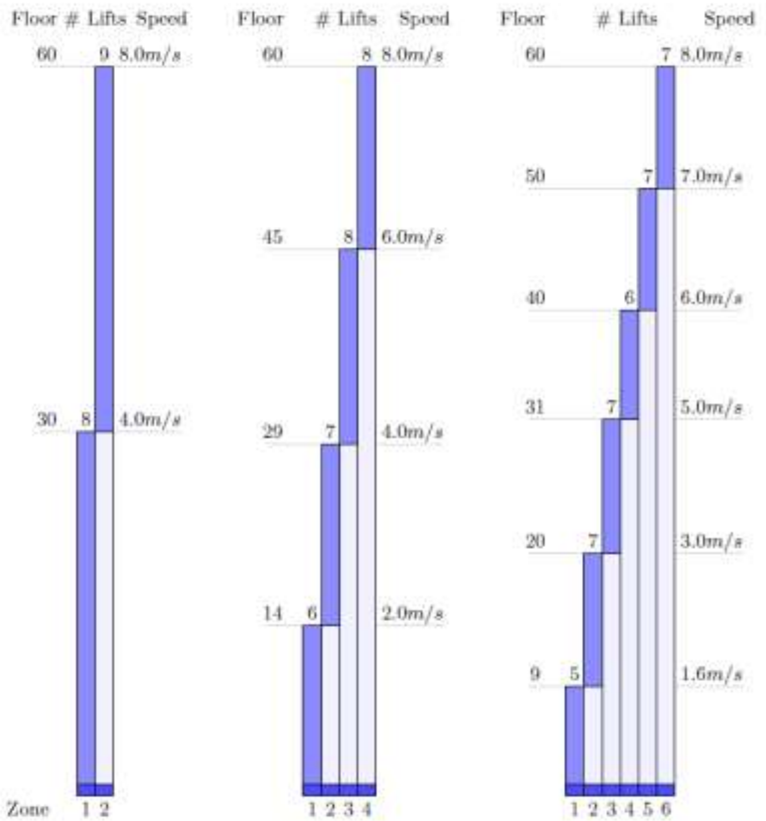

Figure 7 Zoning solutions by optimizing the number of lifts for a 60-floor building with 50 (left), 100 (centre), and 150 (right) persons per floor

4.5 Lift group size distribution

From Fig. 6 and 7 one can see that there is a trend in the number of lifts, they increase as function of zone index, the higher zone the more lifts. Figure 8 shows the division of the number lifts between zones. This is calculated over all optimal solutions (2400 in total) when the core area is optimized, and the results are shown separately for solutions containing 2, 3, .., 10 zones. For example, for optimal solutions containing 2 zones, the lower zone contains about 40 % of the lifts while the upper zone contains 60 %.

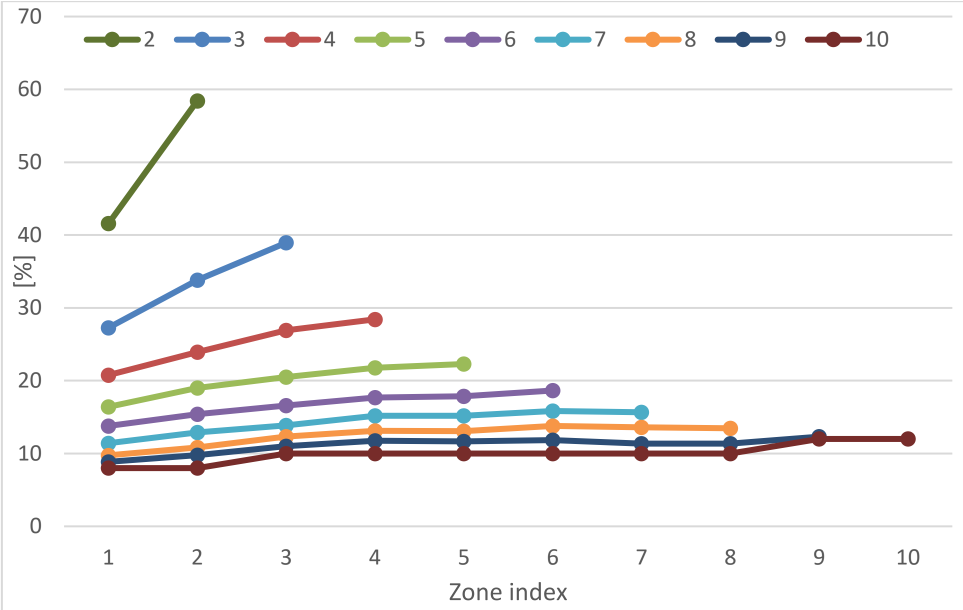

Figure 8 The number of lifts per zone when core area is optimized

5 CONCLUSION

This paper introduced a dynamic programming algorithm to find an optimal lift zoning for a building under design with the conventional control system. Destination control requires a separate consideration. The program models uppeak traffic as a basis of the design. The program minimizes either the maximum filling time, the lift core area or the total number of lifts over all zones. Since zoning reduces the number of stops per round trip, it increases lift group handling capacity. The increased handling capacity, on the other hand, allows area savings in lift core: either some lift shafts can be eliminated or car sizes can be reduced.

Numerical experiments show that the dynamic programming algorithm is capable of defining zones for any kind of a multi-storey building. However, none of the studied objective functions alone may not produce practical zoning arrangements. Thus, the static zoning should be studied as a multi-objective problem or additional constraints should be incorporated in the model. Also, interfloor traffic should be taken into account in the design phase, meaning that lift traffic simulations with group control system are needed. For the maximum filling time and the core area objectives, the optimal solutions consisted of lifts groups with at most eight lifts. This means that the traditional rule for designing lift groups with at most eight lifts with the conventional control has a sound basis.

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BIOGRAPHICAL DETAILS

Mirko Ruokokoski graduated from the Department of Engineering Physics and Mathematics, Helsinki University of Technology in 2008. Currently, he is finalizing his doctoral thesis at Systems Analysis Laboratory in the Aalto University, School of Science and Technology. He joined KONE in 2012 and has been working for R&D.

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Boosting Traffic Handling Capacity in the A♦DAM Tower

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Keywords: lift capacity, multifunctional high-rise, refurbishment, traffic profiles, creative problem solving, simulation, bespoke traffic handling solutions

Abstract. This paper discusses the technical design and traffic handling simulations for the lift system in the transformation of the multifunctional A♦DAM tower in Amsterdam. This former Shell office for 500 employees was refurbished in 2014-2017 for potentially 3,000-5,000 daily users in a dense mix of different (public) functions. It has become an international hotspot for the music & dance industry since. The lift configuration in the tower has been radically redesigned to accommodate this huge increase of traffic (6-10x) through a combination of drastic technical, architectural and organisational measures.

This paper presents these initial measures, as well as the traffic simulations that were performed to analyse their effect. It gives an overview of several practical modifications that were made after commissioning in 2017 to optimise traffic handling even further, based on the size and characteristics of the actual traffic and the waiting times that were experienced in practice. The paper includes the results of a recent traffic measurement and the unique origin-destination matrix that was measured from the actual destination control system.

1 INTRODUCTION

"A♦DAM tower" is a refurbishment project in the North of Amsterdam. This tower was formerly known as "Overhoeks" and is a former Shell office tower. This monumental icon has been transformed in 2014-2017 by replacing the façade, adding a new podium and adding a completely new crown that increased the height to 94 meters. Through this transformation the tower has been given back to the public as a 24/7 leisure hotspot. It has become a tourist attraction and the epicentre of the Dutch Music and Dance industry, which is especially booming in house music and festivals. An impression of the stripped carcass during the transformation and the finished new crown can be found in figure 1.

Figure 1 A♦DAM's stripped carcass (2015) and new crown (2017)

The name "A♦DAM" is an acronym for **A**msterdam **D**ance **A**nd **M**usic and also reflects a common abbreviation of the word Amsterdam. The tower offers a wide variety of functions, such as:

- "Lookout" (indoor and outdoor observation deck on the 20th and 21st floor respectively);
- "Loft" (event spaces, wedding chapel, meeting rooms, members club);
- Boutique hotel;
- Multi-tenant offices (strictly related to the music and dance industry);
- Studio's (recording and short-stay residential);
- Revolving restaurant and other top food & beverage facilities;
- Several clubs and bars.

A vertical section of the multi-functional stacked tower can be found in figure 2.

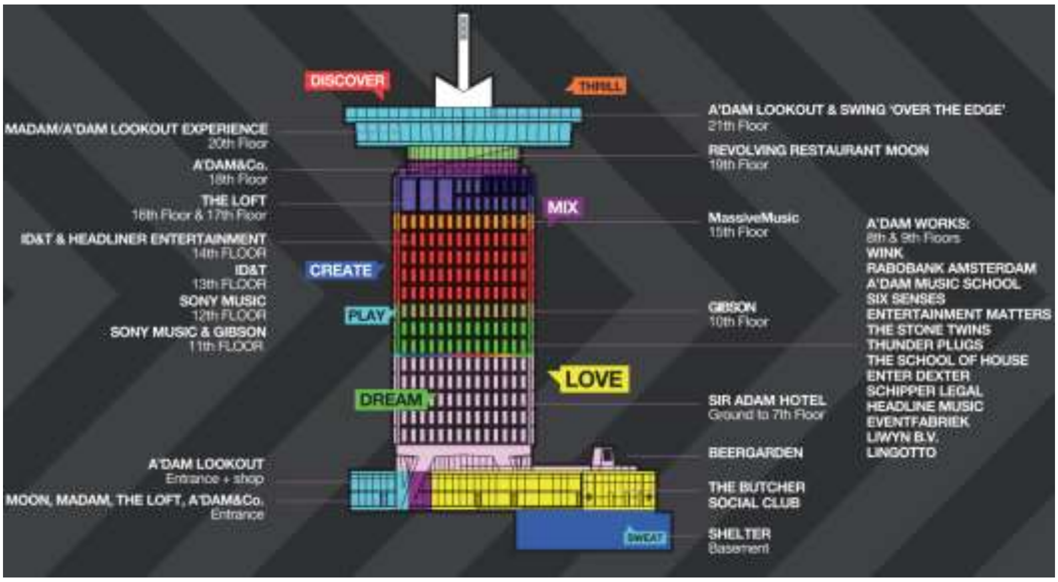

Figure 2 Vertical section of A♦DAM's multifunctional stacked lay-out

2 EXISTING BUILDING AND LIFTS

The tower was originally designed by architect Arthur Staal and opened in 1971. It had an original height of approximately 80 meters and offered four traction lifts with a nominal load of 1,275 kg and a nominal speed of 1.75 m/s. It had conventional group controls and serviced approximately 500 office employees. The tower was sold by Shell to the Amsterdam Municipality in 2009 and offered for sale in a public competition in 2012. A group of investors from Amsterdam (Duncan Stutterheim, Sander Groet, Hans Brouwer and Lingotto) won the competition and transformed the tower into A♦DAM. Figure 3 shows the former silhouette of the building with the modest original crown, figure 4 shows the original lift diagram with stops till the 18th floor.

3 MODIFICATIONS (DESIGN PHASE)

3.1. General

For the new A♦DAM tower the daily number of visitors was anticipated to potentially be 3,000-5,000. This range is due to potential growth in the tourist functions and due to seasonal variations. The tower itself can accommodate approximately 900 people simultaneously, the enlarged 45° rotated crown can hold an additional 600 people. To transport these flows a rigorous change in the lift lay-out and their functional use was required, as well as an unconventional mixing of flows to accommodate the dense, diverse and non-traditional traffic patterns in this building. Fortunately, the client and main users embraced the idea of mixing different user groups in the lifts, because it enforced the sharing character and the 24/7 attitude of the building. This vital measure and several other initial modifications are described in the sections below. The potential gains of multifunctional lift sharing can be found in [1]. A more extensive description of some of the other measures is included in [2].

Figure 3 Overhoeks Shell Tower in 1971, "Tower for sale" in 2012

3.2. Technical modifications

To serve all the new functions in the tower and specifically in the increased public crown the lift lay-out was modified dramatically. The old and new vertical lay-out can be found in figure 4. The horizontal lay-out is shown in figure 5. The following technical modifications were applied to the lift lay-out for capacity reasons:

- The existing lifts 1 through 4 (1,275 kg) were replaced by new lifts A through D with higher nominal speeds of 3.5 m/s (lift A) and 3.0 m/s (lifts B through D);
- The nominal load of lift A was increased to 2,500 kg to serve as the main shuttle lift to the Lookout (observation decks). For these shuttle rides an "Experience mode" on car controlled operation was introduced. This mode provides an enhanced thrill ride, including lighting and sound effects and a higher acceleration/deceleration rate of 1.2 m/s^2. This rate was initially intended to be even higher but appeared limited by the available room for the lift machine;
- The lift group in the existing core was expanded with an extra lift (lift E - 1,275 kg - 1.6 m/s) that serves the hotel levels in the bottom half of the tower;
- The service range of lifts A and D was expanded beyond the existing highest floor (18th floor) to the new crown levels (19th through 21st floor);
- The new 5-group was equipped with destination controls for capacity reasons, due to the diverse range of serviced levels per lift and for easy integration with access control systems;
- To optimise the available capacity in the new 5-group even further, six local lifts (6 through 11) were added in the podium and the crown for wheelchair access, parking and goods storage. These lifts support the handling of local traffic, concentrate the traffic flows and limit the number of stops per cycle in lifts A through E. They also provide the possibility to reduce the number of main entrance floors in the central core to only one (ground floor) and switch off several other levels from normal operation. Only 13 out of 21 upper floors are served in normal operation (including the manually operated Experience mode), the rest is accessible by key-card authorisation (for mobility impaired users and goods), stairs or local lifts only.

Finally, to emphasize the exuberant and welcoming character of the tower and maximise the traveling experience all the lifts have different and in some cases rather extravagant finishing.

3.3. Organisational and architectural requirements

To support the traffic handling even further, the following organisational and architectural arrangements were required:

- The mixing of different types of users in the main 5-group in the tower's core. The flows were merged into combined lobbies and share lifts together. Study had shown that offering dedicated lifts in the tower for all major user groups would require at least 7-8 lifts in the main core. The required space and budget for this solution was not available. Mixing flows increased the handling capacity significantly and was required in this tower. See [1];
- The uncoupling of external delivery times and internal distribution times for hotel, Lookout and Loft, by generally disallowing simultaneous external and internal goods deliveries. For this purpose, access to additional storage area in the basement was introduced by providing goods lifts 7 and 8. This enabled the internal distribution in lifts A through E to be organised within slow hours, mitigating potential capacity shortage in these lifts during peak hours;
- The use of dedicated lifts during specific time windows, for instance for dedicated Lookout service, special events (such as conferences, launch parties and weddings) in the Loft and goods distribution;

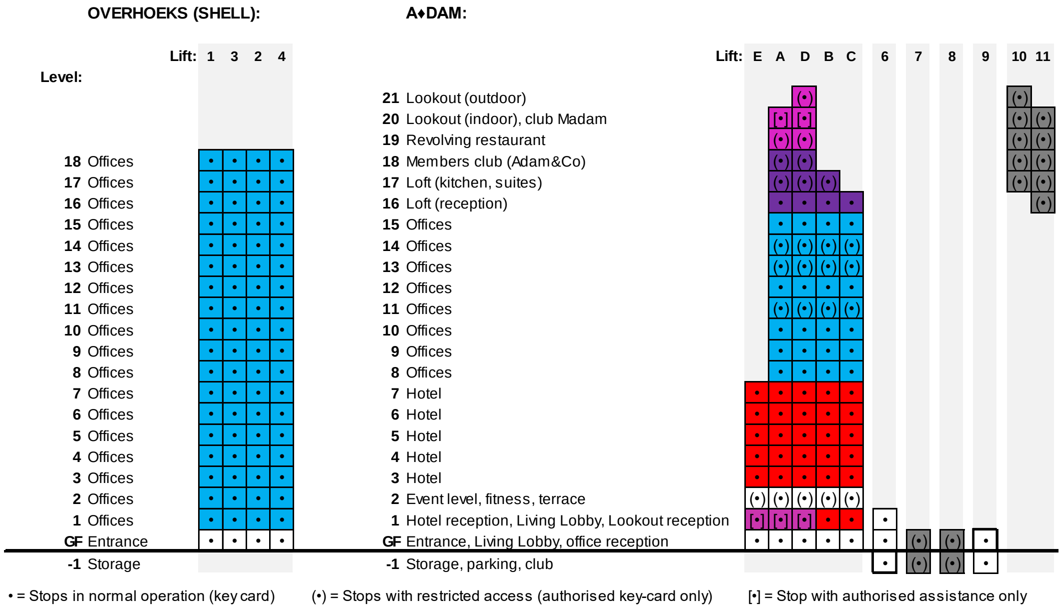

Figure 4 Vertical lift diagram of A♦DAM Tower - before (left) and after (right)

Figure 5 Horizontal lift plan (ground floor, after)

- The positioning of the reception desks for the hotel and the Lookout on the 1st floor, separated from the office reception on the ground floor. This was done to optimise people flow, to concentrate shuttle traffic and for security and commercial reasons. The Lookout received its own reception, lobby and ticketing services on the 1st floor. For this purpose, the lift lobby on this floor was physically split. Figure 6 shows an illustration of this flow separation. These split reception areas and lift home floors for the office/hotel section and the public Lookout section also enable the functional split of A♦DAM into a tower zone and a crown zone. This can be seen in figure 7. No intensive traffic between these zones was originally intended, only authorised VIP and goods traffic.

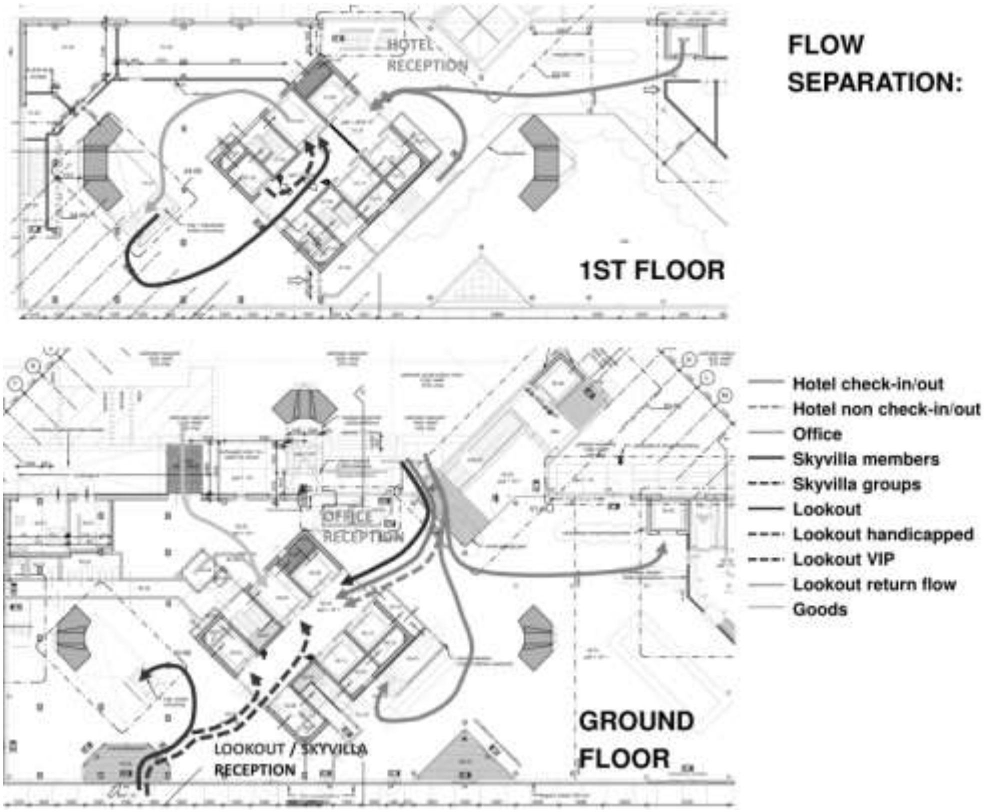

Figure 6 Flow separation: multiple entrances and vertically split main lobbies

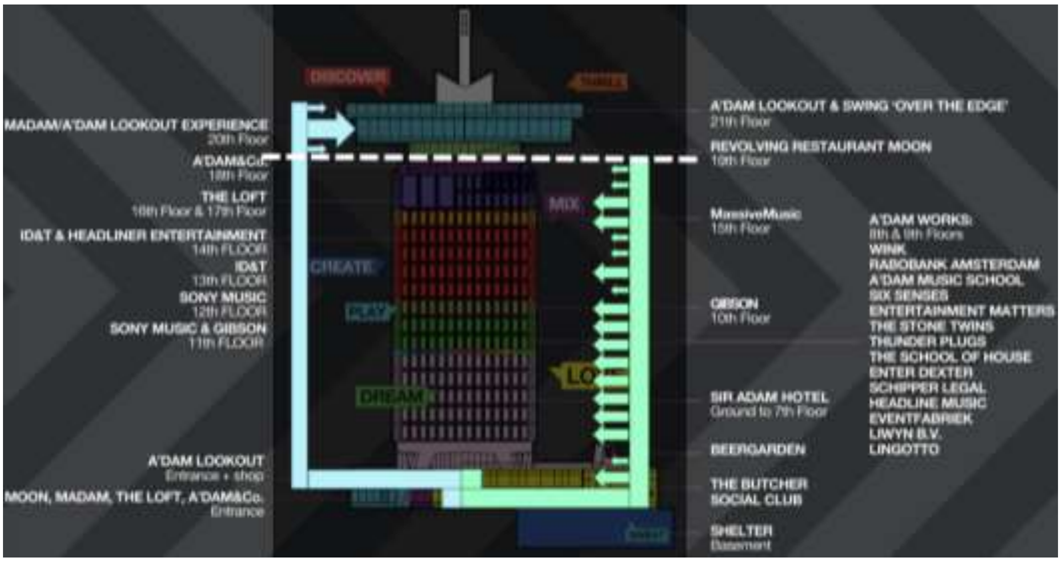

Figure 7 Split main lobbies and zones in A♦DAM: tower and crown

4 TRAFFIC PROFILES (DESIGN PHASE)

The complexity of the originally anticipated traffic profiles in the A♦DAM tower is illustrated in the daily profiles in figure 8. These profiles were estimated with the clients in the design phase, based on the potential traffic density after completion, with a maximum population several years after commissioning. They show the combined anticipated traffic demand for people and goods transportation in the central 5-group.

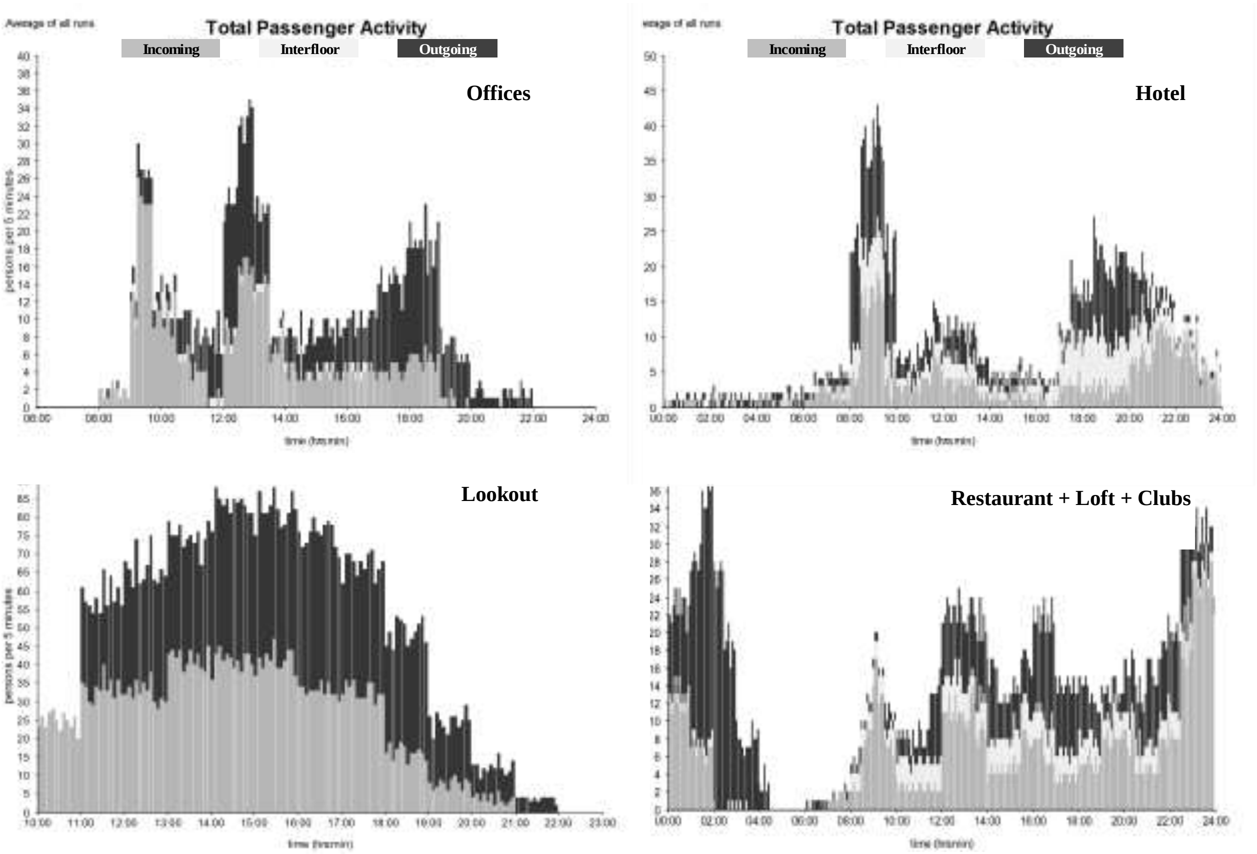

Figure 8 Isolated design traffic profiles per user group

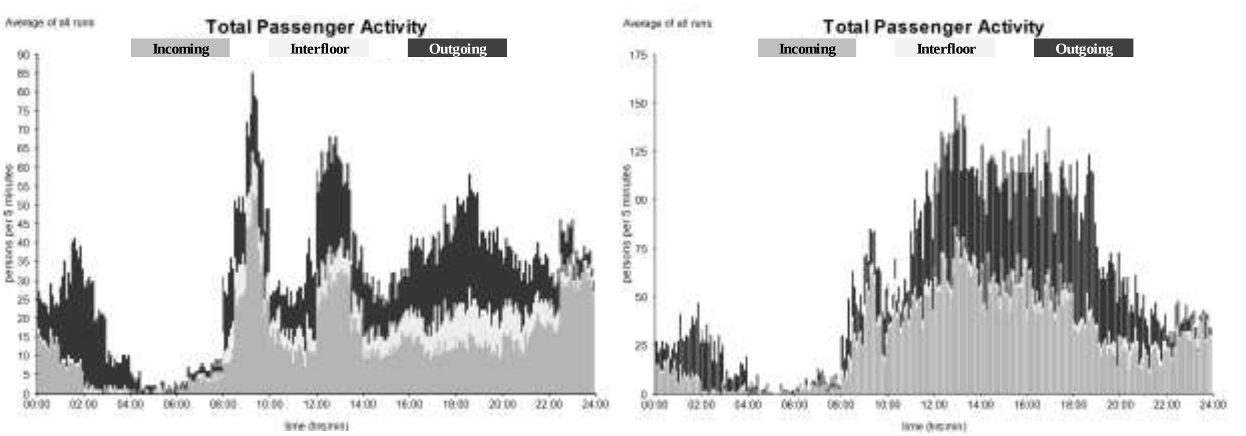

Figure 9 Daily total traffic for A♦DAM: Excluding (left) and including (right) Lookout traffic

The profiles for the office and hotel resemble typical daily patterns for these common functions. The combined profile of the restaurants including the clubs and the Loft is rather unique. The forecast of the maximum Lookout traffic pattern is quite evenly spread during tourism hours, but is dominant in absolute numbers. An average Lookout dwell time of 45 minutes was assumed. These graphs do not yet include any special events, such as conferences, weddings and/or (musical) launch parties. The general idea is that these movements will take place in the Lookout shuttle additionally.

The anticipated maximum number of daily transports studied was approximately 9,000 excluding the Lookout visitor movements and over 16,000 including these movements. The numbers reflect the potential maximum traffic density several years after commissioning. The combined traffic flows in this final phase can be found in figure 9. It shows the daily traffic rhythm prognosis with and without the Lookout traffic.

5 TRAFFIC SIMULATIONS (DESIGN PHASE)

To analyse the effectiveness of the initial design modifications from section 3 and the anticipated traffic profiles from section 4 numerous simulations were performed to identify the potential waiting time development during the day for the final phase traffic [3]. In figure 10 the resulting waiting times predictions are shown with and without the Lookout traffic, but without a dedicated Lookout shuttle. The service without the Lookout traffic will be “excellent”, the combined service including this traffic will be only “moderate” – “poor” in the afternoon.

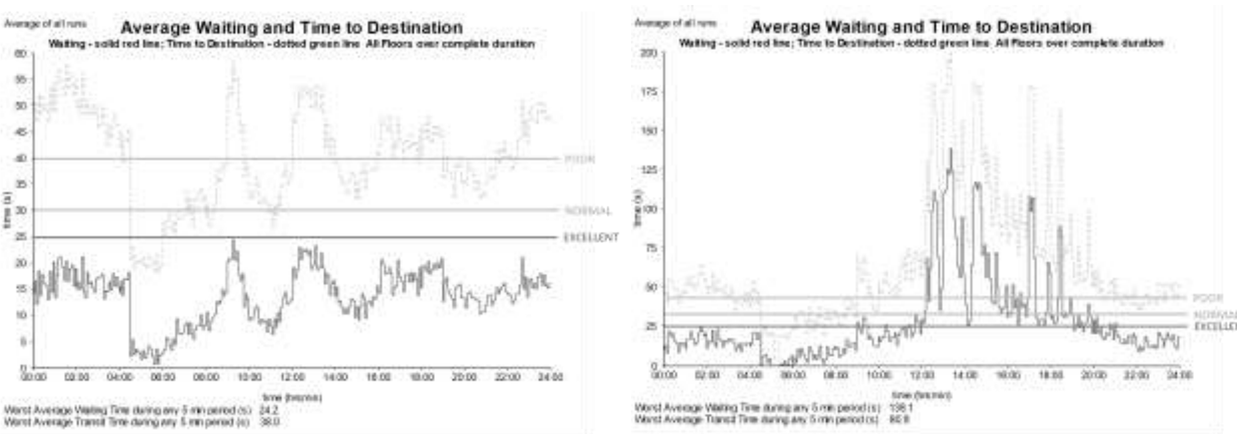

Figure 10 Waiting times without (left) and with (right) Lookout traffic, all lifts A-E available (no dedicated Lookout shuttle)

In figure 11 the intense Lookout traffic has been isolated in a dedicated shuttle lift. This shows to be advantageous in the afternoon for all users involved, especially during the Lookout peak hours.

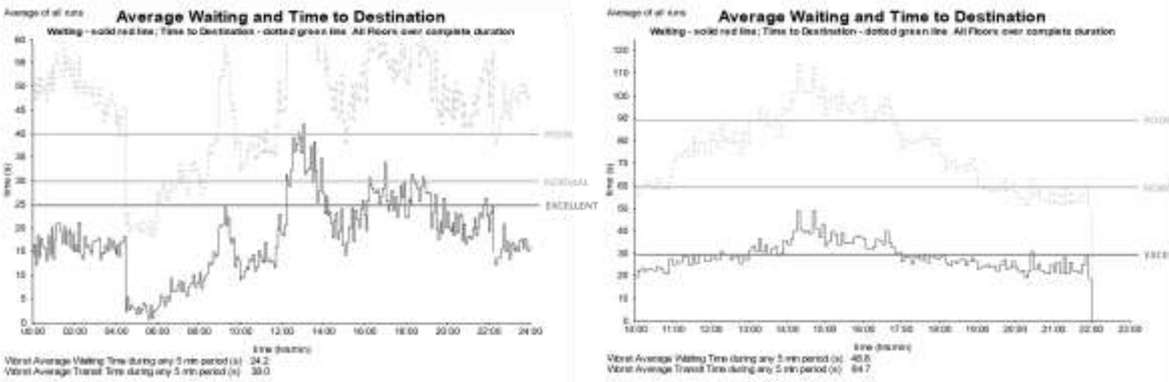

Figure 11 Waiting times in lifts B-E without Lookout traffic (left) and dedicated Lookout traffic in shuttle lift A (right).

6 CONCLUSIONS AND RECOMMENDATIONS (DESIGN PHASE)

From the design phase traffic analysis and lift simulations with the maximum future population the following conclusions were drawn for serving the full population on a busy day:

- The transportation capacity will be sufficient for normal busy day operation. The set of technical modifications, organizational restrictions and broader opening hours (compared to standard office use) provide a potential capacity boost of over 800% compared to the initial traffic handling of the original Overhoeks lift system;
- To serve the potential Lookout traffic in A♦DAM a dedicated shuttle will be required;
- Even with the maximum population present the average waiting time over the whole day will be approximately 30-40 seconds, which should be considered adequate for this multifunctional (existing) tower;
- In the morning peak waiting times will be “excellent” (20-25 seconds), but only if the Lookout shuttle is available to assist in the busiest combined peak hour between 8:00 and 10:00 h (office and hotel peak). During lunch hours and the afternoon/evening peak the waiting times will be “normal” (30-40 seconds). Lookout visitors will have an average waiting time of 30-50 seconds, which can be considered “excellent” for such a feature. Some users will however experience 2-3 times higher waiting times on levels with a reduced number of lifts in service (mainly on the 1st, 17th, 18th, 19th and 21st floor);
- The highest waiting times will potentially be encountered during the lunch peak, while the office has its dominant peak, several restaurants are open (including hotel services) and the Lookout shuttle is in dedicated operation for the observation deck guests.

From the provisional traffic analysis, the following organisational recommendations were made:

- The Lookout shuttle is required to assist lifts B-E for handling the combined hotel and office morning peak between 8:00 and 10:00 h. These functions have their breakfast peak (two-way traffic) and incoming peak more or less simultaneously, even though the office peak will take place significantly later than in regular office towers, due to the nature of the business involved (music and dance scene);
- The above mentioned morning peak restricts the Lookout opening hours to start no earlier than 10 h. After the morning peak a dedicated shuttle can then be made available during Lookout and club opening hours from 10:00 h till 6:00 h the next morning. During

weekends and holidays lift D can join the shuttle service for more capacity. On these days, this lift can be removed from regular service because the offices will be scarcely populated;

- A dedicated time window for goods transportation for all functions is required. Goods can be distributed in lift A in a restricted early morning window between 6:00 and 8:00 h. The transport capacity in this two hour time window is sufficient for all anticipated 150-175 daily goods movements. For incidental hotel back-of house flows outside of this window lift E can be used to a limited extent;
- It is crucial to introduce a reliable means of access control in the main lift core, to prevent unauthorized users from misusing the system by selecting direct travels to stops that have been restricted for capacity reasons. Also, the potential “lift tourism” due to the anticipated attraction of the tower and interest in other lifts (all lifts have unique finishing) than the Lookout shuttle has to be prevented;
- Peak traffic for special events will preferably have to be handled in the Lookout shuttle (lift A). During the day there will be sufficient capacity in this lift to allow momentary shuttle rides to the primary event areas on the 2nd and 16th floor. The waiting times for Lookout guests will obviously increase momentarily, but this is acceptable for such an attraction. Special events should not start before 10:00 h to prevent waiting time interference with the hotel and office morning peak;
- The issuing of key-card authorisations after commissioning should start strictly and conservatively to allow for optimal traffic handling conditions for all parties involved. Only if the (initial) traffic handling volume and/or waiting times are lower than anticipated these authorisations can be issued more freely.

All above recommendations were integrated into the design. Special attention was given to the intelligent integration of the lift destination control system and the building overall access control system through key card authorisation. A wide range of different authorisation levels on personal cards was negotiated with all user groups. Cards are issued with individual and adjustable authorisations to provide customised clearance to otherwise closed-off levels in the tower. Authorisation is granted through the destination control consoles with integrated card readers.

7 TRAFFIC HANDLING (REALITY)

After the phased commissioning of the tower in 2016-2017 traffic measurements and visual observations were performed in May 2017 to analyse the actual use of the lifts and traffic handling quality. The following observations were made:

- The Lookout traffic was initially less intense than anticipated, while traffic handling for all other functions was close to saturation at times. This was not caused by a higher than expected traffic density, but mainly by the following deviations from the original setup:
  - There appeared to be an improper degree of authorised travelling to/from limited access levels, resulting in suboptimal traffic conditions. Partially this was caused by the insufficient restriction in the issuing of cards. Also, the anticipated integration with the required access control systems was not delivered on time and not tuned correctly. This caused leaks in the system;
  - For special events lifts B, C and D were often used instead of Lookout lift A;
  - The strict separation between the tower and the crown section was not maintained stringently: over 8% of the traffic appeared to be interfloor traffic between these zones. Office and hotel guests were offered direct trips to/from the crown instead of using the dedicated shuttle from the podium lobbies;
  - There was a lot of interfloor traffic between the crown floors and the 8th floor, where the back-of-house and office for the Lookout and Loft had apparently been located without

consultation. This conflicted with the intended zonal separation between tower and crown (see figure 7);
    - There was a lot of interfloor traffic between the kitchen on the 17th floor and food & beverage functions in the crown. These flows were supposed to use stairs and goods lifts 10 and 11 only;
    - There was a lot of interfloor traffic between the 11th - 14th floor, which was intended to be a 4-floor segment for one dedicated tenant. These floors were supposed to be connected by stairs only from a local reception on the 12th floor;
    - The revolving restaurant on the 19th floor was being served from the ground floor directly through lift D, instead of indirectly by the Lookout shuttle lift A from the 20th floor by stairs;
    - Lift D could be called from the 21st floor directly. This stop was intended for authorised transportation of mobility impaired guests and goods only;
- Doors were often held open by users and even physically blocked for goods and remaining construction/modification transportation, resulting in a decreased availability for all users and a higher failure rate;
- Lifts were cleaned and serviced/modified during peak hours;
- A substantial amount of ghost passengers (people boarding a car without having put in their destination call first) was observed: approximately 10-20% depending on the time of day;
- The volume of transported goods to/from the food & beverage functions in the crown turned out to be three times higher than indicated in the design phase.

Based on the observations the following immediate modifications were advised:

- Extend the goods transportation window to 8:30 h (implemented);
- Introduce nudging of the doors to activate forced closing (implemented);
- Include the 21st floor as an authorised floor and/or deploy permanent personnel for guidance here (implemented);
- Instruct kitchen personnel once again to use the stairs and the goods lifts 10 and 11 only (implemented);
- Shift cleaning and servicing of the lifts to moments outside of peak hours (implemented);
- Apply a stricter policy in issuing key-card authorisations and revoke incorrectly issued cards if possible to prevent suboptimal lift use (implemented);
- Relocate the Lookout & Loft offices in the crown area (preferably to the 16th or 18th floor) instead of on the 8th floor (not implemented);
- Enforce a higher use of stairs in the office zone between the 11th and 14th floor (not implemented).

Based on the potential traffic capacity that should become available when incorporating the optimisations above correctly the following modifications were allowed on client request:

- Allow limited authorised hotel traffic between the ground floor and the 1st floor (reception), although the use of lift 6 is still preferable for this flow (implemented);
- Allow limited traffic directly to the 19th floor restaurant by lift A, although access through stairs from the main Lookout level on the 20th floor is still preferable (implemented);
- Allow groups travelling to/from events in the Loft to use the Lookout shuttle lift A (implemented);
- Allow limited and guided traffic flows for direct access between the Loft and Lookout floors (including restaurant guests) by selling combi tickets with VIP access cards for certain high-profile events (implemented).

8 RECENT MEASUREMENTS

In 2018 the tower can be considered a commercial success in terms of media attention, events and visitor numbers. The restaurants and hotel are usually sold out, offices are fully rented out and event facilities are crowded almost every week. These events tend to dominate the weekly and daily fluctuation in traffic flows. To evaluate the current traffic handling quality the earlier traffic measurements were repeated in May 2018. Data from a 12-day period was extracted from the destination control system [4]. The graphs in the figures 12-16 below were built up from the retrieved data over this period [1)]. Some interesting numbers and observations from the DCS controller data for lifts A through E are:

- The number of registered calls was approximately 45,000 in 12 days and over 4,800 on a peak day (Friday);
- The number of motor starts was approximately 68,000 for 5 lifts in 12 days. For lifts B through D it was between 1,500 and 1,900 per lift on a peak day (Friday);
- The total number of people and goods moved on peak days was 9,000-9,500 in the 5 DCS lifts combined;
- The number of Experience mode trips for Lookout shuttle A was approximately 7,350 in 12 days. On peak days over 5,200 extra visitor movements were handled on car control mode;
- The average waiting time over 24 hours was approximately 23 seconds and the average destination time was approximately 64 seconds (excluding Lookout shuttle service in lift A). In peak hours these numbers increase to approximately 30-35 seconds and 75-85 seconds respectively. On peak days the average waiting time increases further by approximately 20-30% and the average destination time by approximately 15-20%;
- The peak hours appear to be the morning peak (9:00 – 10:00 h) and the late afternoon peak (17:00 – 19:00 h) instead of the originally assumed critical lunch peak. Waiting and destination times in the afternoon peak are the highest, because lift A is in Experience mode handling Lookout traffic at that moment;
- The waiting and destination times to/from the 18th – 21st floor are indeed substantially higher since only a limited number of lifts serve these floors;
- There is still a substantial amount of traffic to/from the floors that are supposed to have a limited accessibility only through key-card authorisation (approximately 17%). This offers room for improvement.

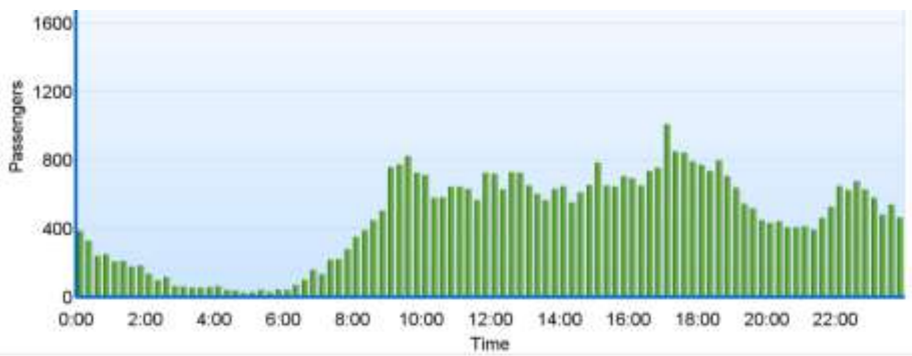

Figure 12 Daily profile of DCS registered movements (© Kone)

[1)] Please be aware that a substantial amount of ghost passengers and most Lookout visitors (handled during activated Experience mode of lift A on manual car controls) are not /included in these graphs. Also these graphs include all traffic over 12 days, without focussing on peak days which appeared to be 20-30% more dense than average days.

Figure 13 Daily profile of waiting and destination times (© Kone)

Figure 14 Distribution of motor starts over the day (© Kone)

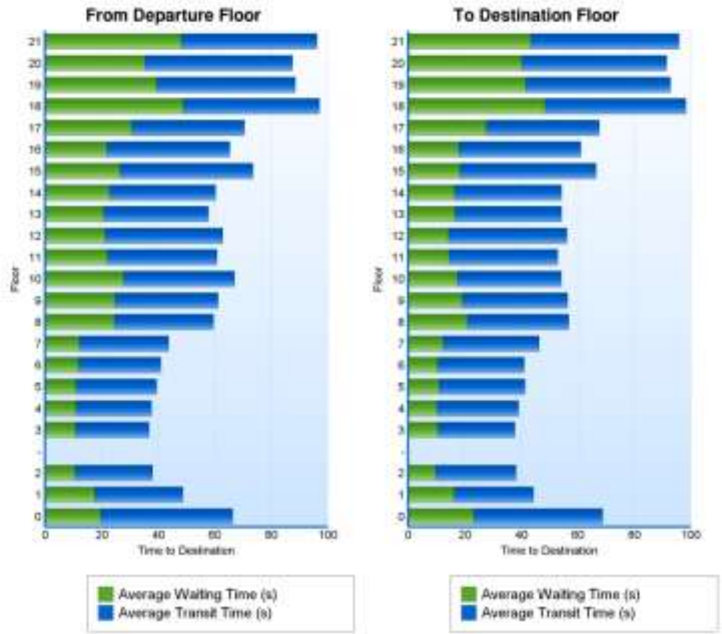

Figure 15 Distribution of waiting and destination times over the height of the tower (© Kone)

	GF	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	TOT
GF	0,0	0,6	0,5	1,1	1,1	1,2	1,2	1,1	2,5	1,0	0,4	0,3	1,4	1,2	1,2	1,4	2,8	2,0	2,7	1,6	[illegible]	0,3	[illegible]
1	0,8	0,0	0,1	0,6	0,8	0,8	0,8	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	[illegible]	0,2	10,9
2	0,8	0,3	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,2
3	1,3	0,8	0,1	0,0	0,2	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,6
4	1,3	0,8	0,1	0,3	0,0	0,1	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,8
5	1,5	1,0	0,1	0,1	0,2	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,0
6	1,4	0,8	0,1	0,0	0,1	0,3	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,0
7	1,4	1,1	0,1	0,1	0,1	0,1	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,2
8	2,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,2	0,2	0,3	0,1	0,1	0,0	3,6
9	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,1	0,1	0,0	0,0	0,0	1,9
10	0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5
11	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5
12	1,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,5
13	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,8
14	1,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,8
15	1,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	2,2
16	3,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,2	0,1	0,5	0,0	5,2
17	1,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,2	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,1	0,3	1,0	0,1	4,0
18	3,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,1	0,0	0,0	0,0	0,0	0,0	0,4	0,0	0,1	0,0	0,1	0,3	0,0	4,4
19	1,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,3	0,1	0,0	0,1	0,0	2,6
20	4,7	[illegible]	0,0	0,0	0,0	0,0	0,1	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	1,2	0,2	0,0	0,0	0,3	12,8
21	0,4	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,3	0,0	0,8
TOT	[illegible]	11,2	1,2	2,2	2,6	2,6	2,8	2,6	3,8	1,8	0,5	0,5	1,6	1,9	1,8	2,0	4,4	4,4	4,1	2,2	11,8	0,9	100,0

Figure 16 Origin-destination matrix for all traffic (© Kone, [5])

9 FUTURE PROSPECTS

The tower's traffic volume is now at approximately 60% of the anticipated maximum design potential. This is already more than 4x than the original traffic volume handled in the former Overhoeks office configuration. The current quality of traffic handling is excellent and there is room for anticipated further growth in the coming years. That will be necessary, because especially the Lookout attendance will presumably grow due to the following recent developments:

- The opening of the North-South metro line in July of 2018, connecting A♦DAM's location to the city centre conveniently;
- The opening of the THIS IS HOLLAND (3D theme ride) pavilion right next to A♦DAM and the Eye Film Museum, establishing the location as a growing touristic hotspot in the North of Amsterdam in the coming years. Combi-tickets are already available;
- The inclusion of A♦DAM as a recommended must-see in a growing number of (international) tourist sites and brochures.

Should traffic handling become problematic in the future after all the following optimisations are still available (based on the traffic distribution presented in figure 16):

- Eliminate interfloor traffic between the 8th floor (Lookout & Loft office) and the Loft/Lookout floors by relocating these offices to the crown zone mandatorily;
- Add attractive internal stairs between the 13th and 14th floor;
- Block the lift stops on the 2nd through 15th floor in lift D, to free up more of its capacity for the crown area traffic;
- Restrict the amount of authorised member traffic to/from the 18th floor directly by falling back on the original concept (stairs from the Loft reception on the 16th floor);
- Fall back on some of the other original game rules by revoking the allowed deviations regarding for instance the mixing of flows between the crown and the tower and direct access to Loft and Lookout levels other than the 16th and 19th floor;
- Recall a significant fraction of the issued key-card authorisations to eliminate suboptimal traffic handling to/from closed off floors.

Since this tower appears to be functioning like a living organism - it evolves with changing use and the internal flows evolve accordingly – future changes in the traffic handling concept will be almost inevitable. There is and there should be sufficient traffic handling capacity to accommodate this.

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BIOGRAPHICAL DETAILS

Jochem Wit received his MSc degree in Mechanical Engineering with honours from the Technical University of Delft in 1995. He is a transportation and lift logistics consultant at Deerns. He specialises in lift capacity analyses, simulations and logistical studies for the optimal dimensioning of lift groups in high-rise buildings, complex stacked buildings and hospitals. In recent years he has focussed on evacuation using lifts and solving saturation problems in under lifted / over populated buildings. He works at the Transportation & Logistics department of Deerns, an expert group in the field of building related transportation equipment. Jochem Wit was a member of the Technical Committee of the Dutch High-rise Covenant and chairman of the Technical Subcommittee for Vertical Transportation. He was consultant for the lifts and façade maintenance equipment for A♦DAM Tower in Amsterdam.

Determining the Number of Simulations Required for Statistically Valid Results

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Keywords: lift, elevator, simulation, dispatcher, Monte Carlo

Abstract. Lift simulations use a random number generator to create a list of passengers based on anticipated passenger demand. Depending on the random number seed, different lists of passengers and resulting lift journeys will occur. Each random number seed scenario yields a different simulation run with different results. An infinite number of runs would yield results including a mean average waiting time and standard deviation which would be fully representative of the data. But only a finite number of runs can be completed as there are practical limitations on time and processing resources. How many runs need to be completed until the mean average waiting time can be said to be statistically valid? Different approaches to assessing the number of runs required for statistically valid results are proposed and discussed. The preferred approach allows the user to specify the required confidence level and acceptable range. The method can be applied to both dispatcher-based and Monte Carlo simulation.

1 INTRODUCTION

1.1 Passenger generation

Simulation software creates a list of passengers based on anticipated traffic demand required by the user. Different approaches to how these passengers are generated is discussed by Peters et al [1] [2]. All approaches rely on random numbers to select passenger arrival times, origins and destinations reflecting the passenger demand.

As the use of random number generators introduces an element of chance, enough passengers need to be considered for an analysis of the average waiting time (or other quality of service parameter) to be valid. If the sample size (number of passengers) is insufficient, the results may be over optimistic or over pessimistic.

1.2 Dispatcher-based simulation

For dispatcher-based simulation, some designers propose a long simulation at constant demand to achieve sufficient sample size result. For example, the draft ISO 8100-32 suggests a simulation of at least 120 minutes, excluding the first 15 minutes and the last 5 minutes of each simulation from the results to avoid the influences of start and end effects, see Figure 1.

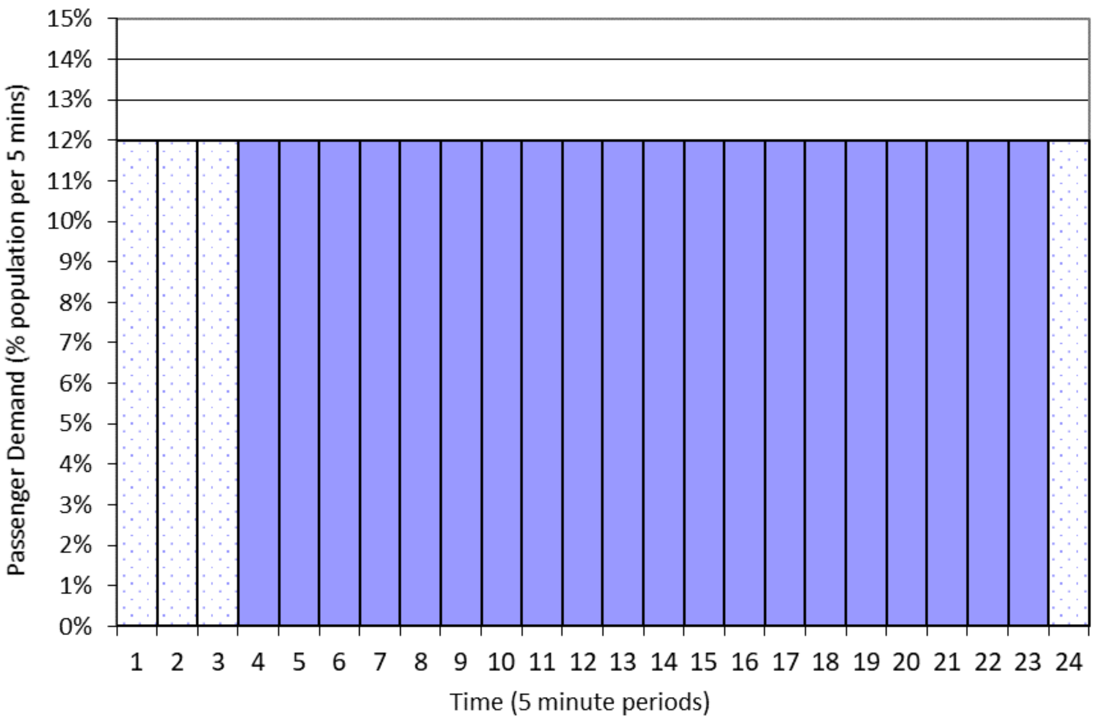

Figure 1 Passenger Demand for constant passenger demand template with first 15 minutes and final 5 minutes results disregarded

CIBSE Guide D [3] recommend designers use templates to reflect the rise and fall of passenger demand at peak times, see Figure 2, but repeat the simulation multiple times (typically 10) with different sets of passengers. Start and end effects can be disregarded as the designer reports results for just the peak 5 minutes of the profile.

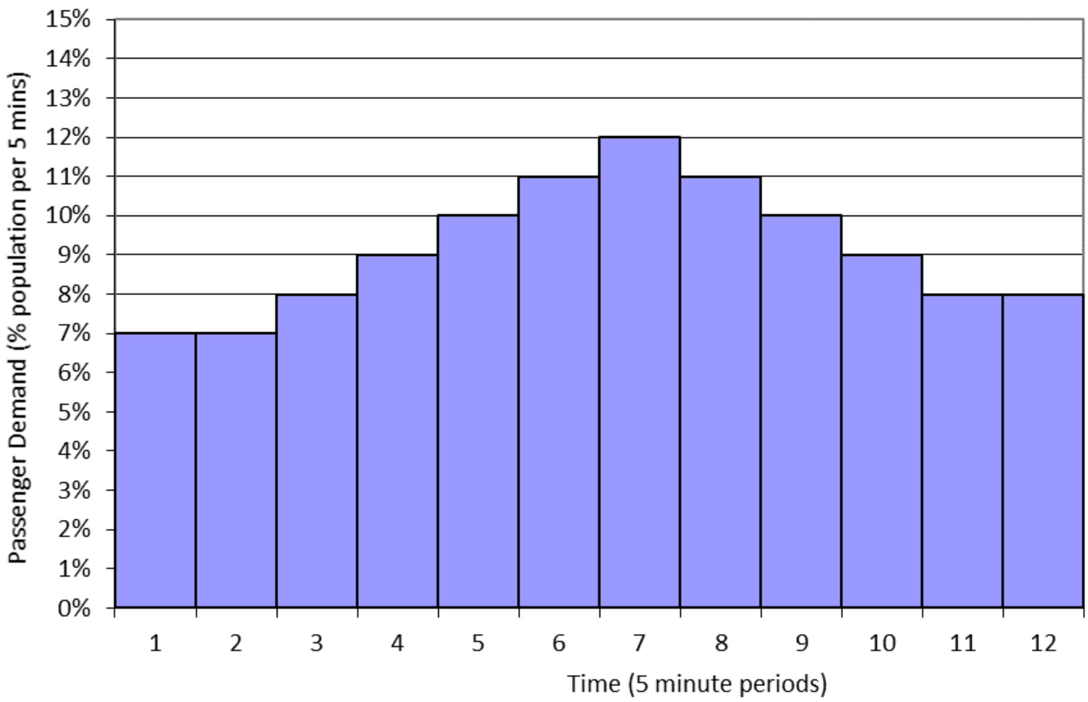

Figure 2 Passenger demand template rising and falling from peak

Both approaches work most of the time and yield relatively stable results. But sometimes 120 minutes (draft ISO 8100-32) is not long enough, or 10 simulations (CIBSE Guide D) is not enough for stability, which can be seen in counterintuitive results. For example, increasing the lift speed may increase the average waiting time. This can occur if increasing lift speed makes little difference because the travel distances are short; in which case the benefit can be so small it is lost in statistical noise.

1.3 Monte Carlo simulation

Monte Carlo simulation [4] creates a travel plan for individual round trips. Each travel plan is known as a trial. Multiple trials are completed, and an average round trip time is calculated. If enough trials are completed, the results become stable.

1.4 Objective

Running too few (or too short) simulations risks the possibility of an unrepresentative conclusion. Running too many or too short simulations is time consuming and wastes resources. This paper explores how to determine how many simulations or trials are necessary.

2 CONSISTENT VALUE (CONVERGING) MOVING AVERAGE

One solution would be to take the moving average of each Average Waiting Time (AWT) result produced by each subsequent simulation. As the number of simulations, n, increases, the percentage difference between each average decreases, showing that the moving average is converging. This approach has been tested by considering 1000 simulations, 4 lifts, and up peak traffic arising from 600 people. Results are presented below.

Table 1 Moving average

Simulation	AWT (s)	Moving average of AWT (s)	Difference in moving average (%)
1	6.1	6.1	
2	4.4	5.3	13.9
3	4.1	4.9	7.3
4	5.5	5.0	3.3
5	7.4	5.5	9.5
6	5.1	5.4	1.2
7	4.8	5.3	1.7
8	5.4	5.4	0.1
9	7.4	5.6	4.3
10	7.0	5.7	2.5

However, as seen in Table 1 and Figure 3, the moving average is subject to large variation. Because the moving average can both increase and decrease as it converges (i.e. not converging as if an asymptote), it also leaves an arbitrary decision as to how many repeated consistent values of the moving average are required before the user is confident in stating that convergence has been achieved; or, for example, what percentage difference is acceptable.

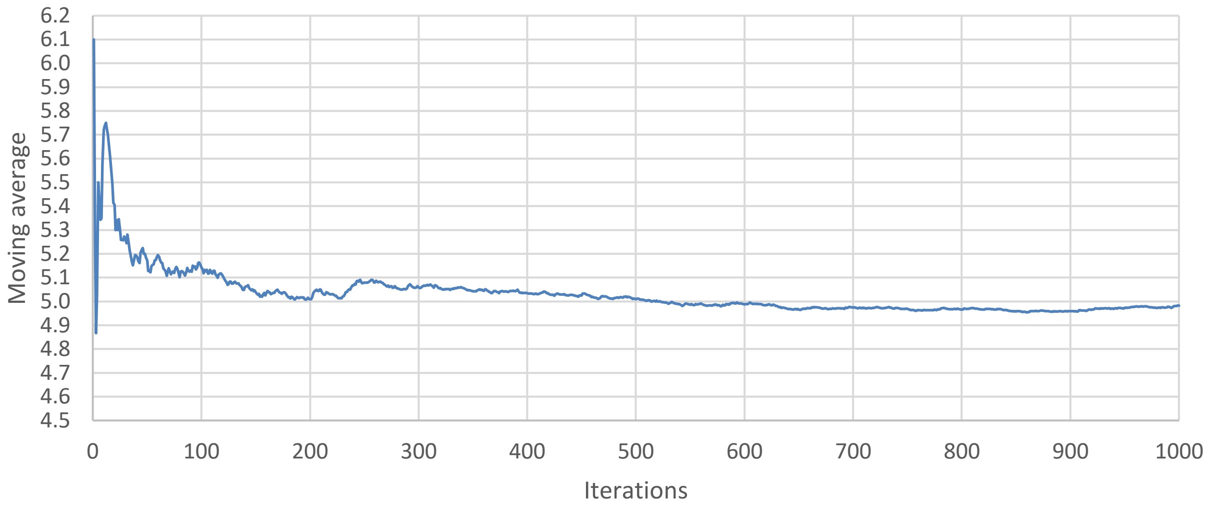

Figure 3 Moving average

The weakness of this technique is that there can be no guarantee of how representative the calculated mean is of the population. For example, consider the simulation results in Figure 3 and corresponding plot of differences in the moving average given in Figure 4: after 15 iterations the mean is 5.6 s. From 500 to 1000 simulations, the average remains around 5.0 s. However, it is quite possible that for 1000 to 2000 simulations, the mean begins to trend upwards again. Having no estimate of how likely the parameter is to be close to the population parameter is a disadvantage, because it is unknown how much confidence can be held in that result.

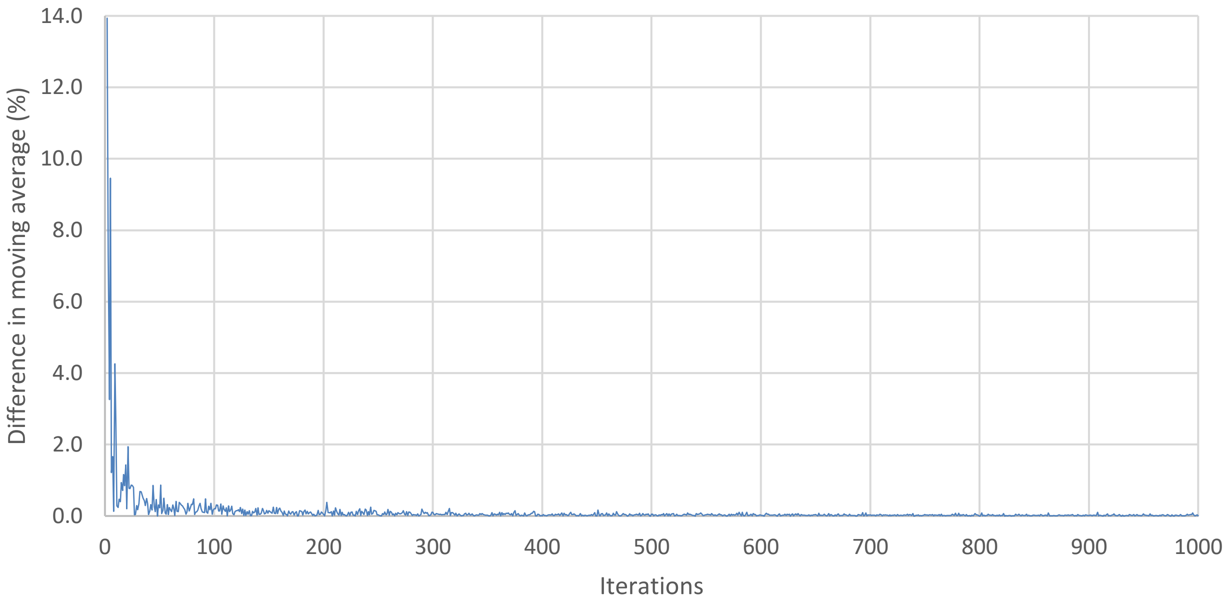

Figure 4 Difference in moving average (%)

3 CONFIDENCE INTERVALS

3.1 About confidence intervals

In statistics, the population is the total set of observations that could be made. A sample is part of that population. In lift simulation it is not practical to consider the total set of observations. As a result, the mean cannot be determined exactly, and an estimate is needed. Confidence intervals [5] are used to determine how close the statistical estimates of the parameters of a population are to the actual population parameters and the confidence that can be held in that determination. A confidence level is the probability that the confidence interval contains the true value of the parameter.

For example, if after 10 simulations (a sample) we calculated the AWT is 5 seconds (estimate of mean), we may determine with 90% probability (confidence level) that, if we ran an infinite number of simulations (the population), the AWT would be between 3 seconds and 7 seconds (confidence interval).

There are various statistical techniques to help calculate confidence intervals and associated confidence levels.

3.2 Probability distribution

To calculation a confidence interval, probability distribution needs to be considered. A probability distribution is a "mathematical function that provides the probabilities of occurrence of different possible outcomes in an experiment" [6].

The probability distribution of AWTs determined by simulation varies for each lift configuration and set of simulation parameters (length of simulation, number of people, number of floors, number of lifts, etc.). These distributions are Lognormal (see Figure 5) rather than Normal (see Figure 6) as the AWT can never be less than or equal to 0s, whereas right tail can theoretically be infinitely long. A Lognormal distribution is "a continuous probability distribution of a random variable whose logarithm is normally distributed" [7].

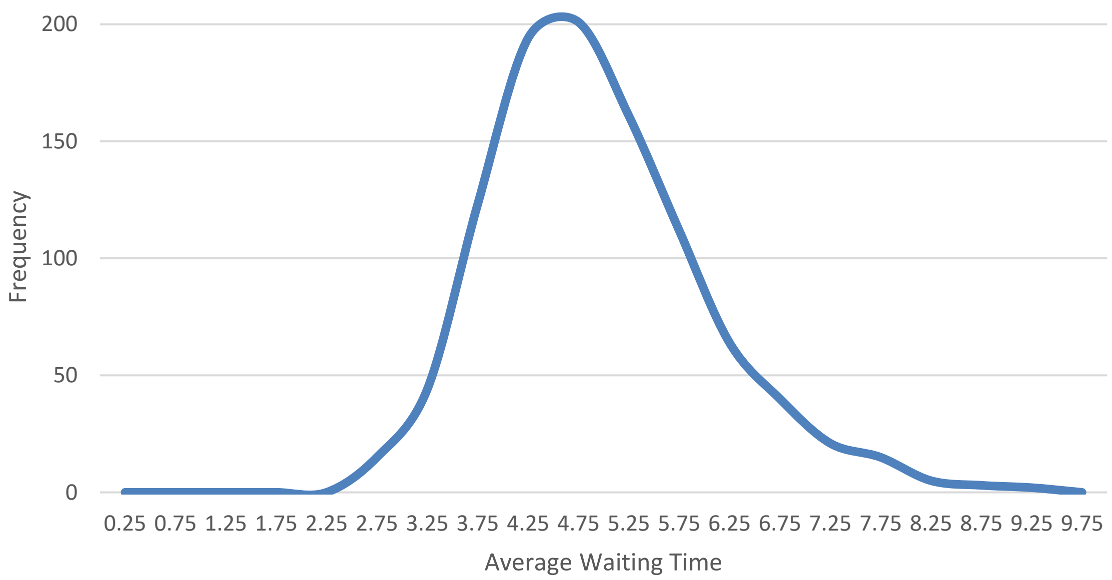

Figure 5 Distribution of AWT for simulation example

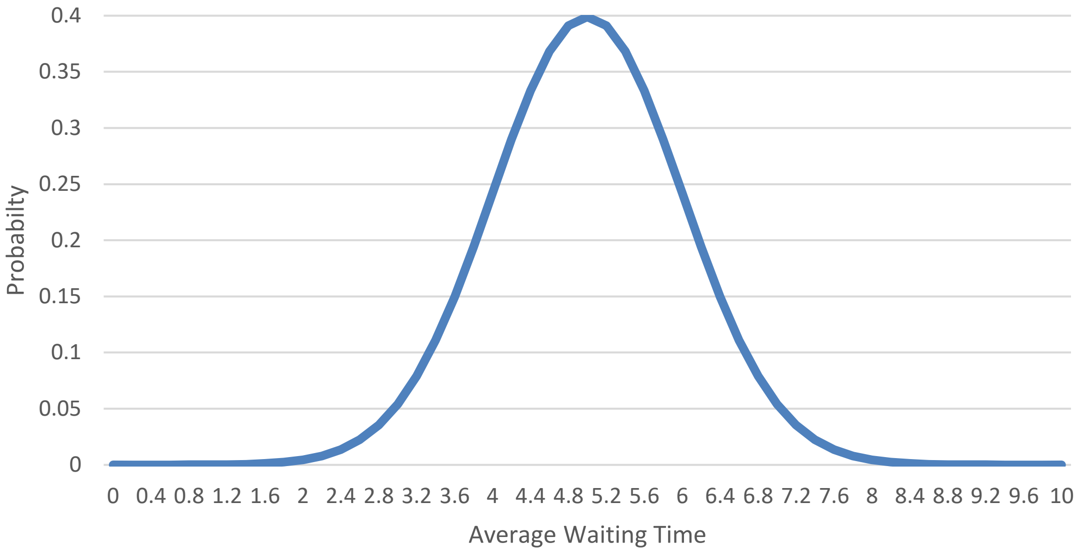

Figure 6 – Normal distribution

3.2.1 Cox method

Olsson [8] presents Cox's method for calculating confidence intervals for data with a Lognormal distribution.

The Cox method requires that the variable x is transformed to $y = \ln(x)$, before sample parameters are calculated.

$$\bar{y} + \frac{s_y{}^2}{2} \pm z\sqrt{\frac{s_y{}^2}{n} + \frac{s_y{}^4}{2(n-1)}} \tag{1}$$

Where $\bar{y}$ is the mean of the transformed data, z is the chosen z-value (Table 2), s_y is the transformed sample standard deviation and n is the number of samples.

Table 2 Confidence levels and corresponding z values

Confidence level				
70%	**80%**	**90%**	**95%**	**99%**
1.04	1.28	1.65	1.96	2.58

When this is transformed back, $\bar{x} = e^{(\bar{y}+\frac{s_y{}^2}{2})}$ within an interval + or – $e^{z\sqrt{\frac{s_y{}^2}{n}+\frac{s_y{}^4}{2(n-1)}}}$.

This method is only valid for large values of n and yields wide intervals. For example, with 1000 simulations and requiring at a 95% confidence interval, the results in Table 3 were obtained.

Table 3 Confidence intervals using Cox method

Number of simulations	Mean AWT (s)	Upper bound AWT (s)	Lower bound AWT (s)
1000	5	36.1	0.7

The Cox method was rejected as the number of simulations required to reach a satisfactory confidence interval is too high to be applied in dispatcher-based simulation.

3.3 Based on Normal distribution

If the probability distribution of AWTs can be approximated as Normal, analysis using the empirical rule [9] and confidence intervals is available.

The empirical rule requires that the mean estimation error is 0 and the distribution of errors is Normal. The D'Agostino test of Normality [10] is inconsistent in its conclusion; sometimes the example data passes the test of being Normal, sometimes it does not. For the purposes of confidence intervals, it is sufficiently close not to be rejected (Figure 5 and Figure 6) [9].

Calculation of two-sided confidence intervals is as follows:

$$\bar{x} \pm z\left(\frac{s}{\sqrt{n}}\right) \tag{2}$$

Where $\bar{x}$ is the mean, z is the chosen z-value, s is the sample standard deviation and n is the number of samples. Guttag states [9] that the mean, $\bar{x}$, is the population parameter within + or – $z\left(\frac{s}{\sqrt{n}}\right)$ with a certain confidence level.

As the number of samples increases, the confidence interval typically decreases. Thus the population parameters are located within a smaller margin. This can be utilised: rather than arbitrarily choosing when the results are converging on the population parameter, one decision on the width of the interval for the location of the population parameter is required. This means each simulation run can use previous simulations to calculate moving sample parameters and each subsequent confidence interval narrows down the exact position of the population parameter.

3.4 Based on t-distribution

For the first simulations, n is not sufficiently large for the Normal distribution to be used, so instead the t-distribution should be used. Sufficiently large has been determined as $n > 25$ [11]. Or n > 30 as shown in [12]. For the analysis t values should replace z values corresponding to certain confidence levels and degrees of freedom (v) ($v = n - 1$) [11].

Table 4 – Confidence levels, degrees of freedom and corresponding t values

	Confidence level				
v	**70%**	**80%**	**90%**	**95%**	**99%**
1	1.96	3.08	6.31	12.71	63.66
2	1.39	1.89	2.92	4.30	9.93
3	1.25	1.64	2.35	3.18	5.84
4	2.13	1.53	2.13	2.78	4.60
5	2.01	1.48	2.01	2.57	4.03

Calculation of two-sided confidence intervals is as follows:

$$\bar{x} \pm t\left(\frac{s}{\sqrt{n}}\right) \tag{3}$$

Driels et al [11] state confidence intervals (equation 3) should be calculated with $n - 1$ rather than n. However, this is not supported in most of the literature [12] [13] so has not been applied.

Petty [14] suggests that if the standard deviation of the population is unknown, the population standard deviation may be approximated by that of the sample and the t distribution may be used in place of normal distribution. The closeness of t values and z values in the ranges we are considering is such that the impact is too small to be worth considering for lift simulation.

3.5 Conditions for use

For analysis with confidence intervals, the statistics required that the AWT calculated in one iteration is independent of every other iteration. Waiting Times within single simulation are not independent, so this approach using confidence intervals could not be used with a long simulation at constant demand unless there were multiple long simulations.

If the lift simulation is saturated (demand exceeds handling capacity), the distribution of average waiting times will not be Normal or approximately Normal. In this case, the AWT does not need to be determined as the lift configuration should, in any case, be rejected.

4 IMPLEMENTATION

Inputs to dispatcher-based simulation software become:

1. Acceptable range, e.g. ± 2 seconds
2. Confidence level, e.g. 90%

In this case, if the calculated AWT was 5 seconds, multiple simulation would be run until the software can confirm with at least 90% confidence that the AWT is between 3 and 7 seconds. Note: the values given are only for example. The authors anticipate recommended values will be published in future design documents after discussion and review.

This is achieved as follows:

As each successive iteration takes place, the sample of AWTs increases by one. Each time the sample accumulates another AWT the confidence intervals is calculated for the chosen confidence level using the t-distribution method (up to 25 iterations) or Normal distribution method (> 25 iterations). If the confidence interval is less than the acceptable range specified by the user, the analysis is complete and the mean AWT is reported.

A similar approach can be implemented in Monte Carlo simulations using Round Trip Time (RTT) in place of AWT. RTT is assumed to meet the same criteria of Normality; there will be differing reasons for the sample not being exactly Normal, but the approximation is reasonable.

5 CONCLUSIONS

This paper reviews possible ways of choosing how many simulation iterations are necessary to provide a result within an acceptable range with a required confidence. A range of statistical techniques are presented and discussed. The chosen method approximates the population distribution of simulation results to Normal, which the authors consider reasonable and practical.

The technique proposed can be applied to both dispatcher-based and Monte Carlo simulation.

The benefit for users of simulation software is that they will no longer need to choose an arbitrary number of simulations; instead they may specify an acceptable range and confidence level that results are required to satisfy.

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BIOGRAPHICAL DETAILS

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Escalator Weightless Weight Testing: A Case Study from a UK Metro

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Keywords: escalator, weight testing, metro, brake testing

Abstract. The escalator braking system is the most important safety component. It is thus necessary to ensure that brakes are tested at regular intervals in order to ensure passenger safety. Carrying out this test using weights is a very complex, risky and expensive procedure, and thus cannot be carried out regularly. For this reason, a model for a weightless brake testing system has been developed for testing the escalator brakes.

This paper describes the work carried out by the author in setting up a weightless brake testing system for testing the escalator brakes at the Tyne & Wear Metro in the United Kingdom.

The first step was to gather escalator type test data on the four escalator models on the Metro. In the second step, the data from the weight tests was used to build a theoretical mathematical model in MS Excel for the different types of escalators. The model allowed the operator to understand the range of acceptable deceleration values that indicate compliant operational brakes. In the third step, all the remaining 28 escalators (out of the full fleet of 32 escalators) were tested and adjusted without the use of weights. They were adjusted in accordance with the outputs of the theoretical model. In the fourth and last test, a training manual was developed for the testing and adjusting the braking systems. On-site training was carried out for the maintenance staff.

1 INTRODUCTION

This paper describes work carried out by the author for the Tyne & Wear Metro in 2002/2003. The work involved carrying out testing on all the Metro's escalator braking systems, in order to ensure that they meet the European standard requirements.

The Tyne & Wear Metro has 32 escalators that are of four types. They mainly date from the late 70's/early 80's and are all manufactured and installed by O&K/KONE.

The testing was planned and carried out in two parts. The first part included weight testing an escalator of each of the four types of escalators. By carrying out the weight test on that type of escalator, not only was that specific escalator tested and adjusted such that it met all the braking requirements, the data was also used to understand the characteristics of the braking system on that type of escalator design.

The data from these tests was then used to extrapolate what the required brake setting on all other escalators of the same type need to be set during light slip tests in order to meet the European standard.

Light slip tests were then carried out on all other escalators. The brakes were tested and then adjusted in accordance with the EN115 braking performance requirements.

This paper describes how the model that was built for the four different types of escalators and the data from the model was used to adjust the remaining escalators in the fleet to meet the requirements of the European standard, EN115.

Section 2 provides some background about escalator brake testing requirements and the concept of weightless brake testing. Section 3 presents an overview of the brake testing performance requirements as stipulated by the European standards EN115. Section 4 discusses the tools used for the measurement of the deceleration of the escalator under the influence of the various braking systems. Section 5 discusses the results from the weight tests that were carried out on the four escalator types. Section 6 discusses the light slip test results for the remaining 28 escalators and presents a table that can be used as a pass/fail criterion for future brake tests of these escalators. Conclusions are drawn in section 7.

2 BACKGROUND

One of the most important safety devices within an escalator is the mechanical braking system [1]. It ensures that the fully loaded escalator is brought safely to a standstill when required to do so following the tripping of a safety device or the activation of the passenger emergency stop switch. Recent developments have introduced the use of electrical braking systems to complement the mechanical braking systems discussed in this paper [2].

It is generally a requirement that full load weight testing be carried out for new, refurbished and partially refurbished escalators to prove that the braking system is capable of (and has been set up to) arresting the fully loaded escalator running in the down direction at rated speed and bringing it to a standstill within the distances stipulated by EN115 [3].

Weight testing is a very lengthy and costly process. It is carried out when an escalator has been replaced or refurbished or where the braking system has been altered. This is especially critical on public service escalators [4]. Public service escalators are subjected to high level of passenger traffic ([5], [6]) which makes the safety of the brakes even more critical.

It is important to note that another paper assumes the value of 150 kg per step in order to calculate the motor or inverter size [7]. The 150 kg is equivalent to two passengers per step each weighing 75 kg, and is over and above the requirement of [3].

Much research has been carried out on the energy drawn by escalators ([8], [9], [10] and [11]) that have shown that that the power drawn by an escalator in kW can be calculated as follows:

$$P_{NL} = 0.47 \cdot r + 1.74 \qquad (1)$$

where:

P_{NL} is the power drawn by the escalator at rated speed and no load in kW

r is the escalator rise in m

A previous paper [12] has presented a measurement-based-model that allows the prediction of the stopping distance of an escalator under loaded conditions in order to obviate the need for the full load weight testing. Such a model will enhance the level of safety in escalators and allow a more scientific approach to the subject of weight testing and proofing of the brakes.

3 BRAKE PERFORMANCE REQUIREMENTS

The brake performance requirements as set out in the European Standard EN115 only stipulate maximum and minimum stopping distance. The maximum stopping distance relate to the fully loaded escalator running in the down direction. The minimum stopping distance relates to empty stopping escalator (see Table 1).

The rationale for this is that the escalator should not stop too abruptly when empty, so that it does not cause passengers to fall when travelling on it. When fully loaded it should be able to stop within a reasonable distance to protect passengers from a runaway situation.

Table 1 Stopping distance in accordance with EN115

Rated speed	Stopping distance
0.50 m/s	min. 0.20 m; max. 1.00 m
0.65 m/s	min. 0.30 m; max. 1.30 m
0.75 m/s	min. 0.35 m; max. 1.50 m

The American Standard ASME A17.1 specifies the maximum value of deceleration of the escalator, as 0.91 m/s^2.

There is strong evidence to suggest that the maximum value of deceleration is a very good indicator of the passenger stopping comfort [11]. It is believed that the maximum value of the deceleration during an escalator stop is inversely proportional to the risk of passenger falls. EN115 has been re-drafted to specify an additional maximum deceleration requirement of 1 m/s^2 in addition to the stopping distances.

The stopping distance on its own is a poor indicator of brake performance. For these reasons, the tests in this document use the maximum value of deceleration as the indicator of the brake performance. The maximum value of deceleration has been used during the tests as the basis for adjusting the brakes and is also used in the results section later as a pass/fail criterion for the braking system.

4 TOOLS USED FOR MEASUREMENT

The main tool used for measuring the brake performance is the EVA-625 unit from a company called PMT (Physical Measurement Technologies). Although the unit was originally developed to measure vibration in lifts, it has been adapted with a handheld tacho-wheel to carry out direct speed measurements on both lifts and escalators.

The handheld tacho-wheel is held against the handrail while the escalator is running. The escalator is then stopped by pressing the passenger emergency stop switch on the escalator using a switch supplied by PMT. The switch has a contact that is connected to the EVA625 unit. This triggers the start of speed recording by the unit. The point at which the switch is pressed is denoted as the ‘trigger point’ and placed at zero time on the time axis.

The data can then be downloaded from the unit via a serial cable connected to an RS232 serial port on a laptop. A software supplied by PMT is then run on the laptop to analyse the data. An example of the analysis is shown in Figure 1. Three variables are shown against time: Velocity (m/s), Acceleration (m/s^2) and Distance traveled (m). the point at which the switch was pressed is denoted as the trigger point (time=0 s). Data logged 0.5 seconds before the trigger point is also shown in the plot. When the escalator gets to zero speed that point is denoted as the ‘Rest Point’.

The maximum value of velocity, maximum value of acceleration and the distance traveled following the trigger point are all shown on the plot.

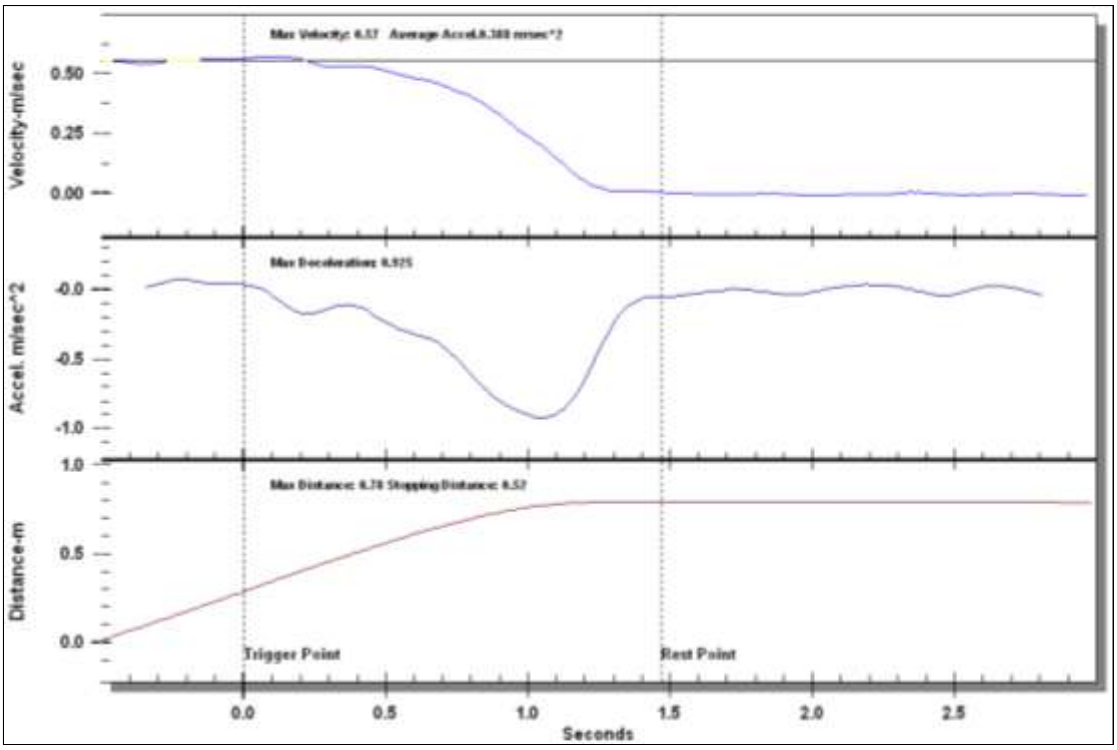

Figure 1 Graphical display on the EVA625 software

It is the maximum deceleration value taken from the software that has been used during the tests as the basis for adjusting the braking system.

5 THE FOUR WEIGHT TESTS

As mentioned in earlier, four weight tests were carried out on four escalator types. A weight tests involves loading the escalator steps with steel weights, running the escalator in the down direction, stopping it and measuring the stopping distance and the maximum deceleration.

The brake load testing is done based on a brake load of 120 kg per step (in accordance with EN115) as the step width is 1 m. The full brake load can be found by using the following formula:

$$L_b = m_s \times \frac{r}{r_s} \tag{2}$$

where:
L_b is the total brake load (kg)
r is the rise of the escalator (m)
r_s is the step rise (0.2 m)
m_s is the applied load per step (120 kg/step)

Prior to placing the weights on the escalator, tests were done with 0% brake load. Then the weight tests were started by gradually loading the escalator with weights in the following sequence: 25% of brake load, 50% of brake load, 75% of brake load and then 100% of brake load and then down in the reverse sequence. A 0% brake load test would then be carried out. Thus the full sequence of tests is:

0%, 25%, 50%, 75%, 100% and then 0%

A 0% brake load test is referred to informally as a “light-slip” test. Each step was loaded with around 180 kg, such that the full load filled around 2/3 of the incline (equivalent to a load per step of 120 kg). The weight tests were carried out on the following four escalator types as follows:

HDM10	18/3/2003
RTV-HD	19/3/2003
HDMS	21/3/2003
Compact	22/3/2003

In order to protect the escalator from the risk of runaway during a weight test the weights are progressively increased and the stopping distance monitored. If a concern arises regarding the capability of the brakes, they are adjusted in order to increase the braking torque.

The results of the weight tests have been summarized as speed versus time plots for the stopping escalator with various loads. The plots have been shown for HDM10 type (Figure 2), RTV-HD type (Figure 3), HDMS type (Figure 4) and the Compact type (Figure 5).

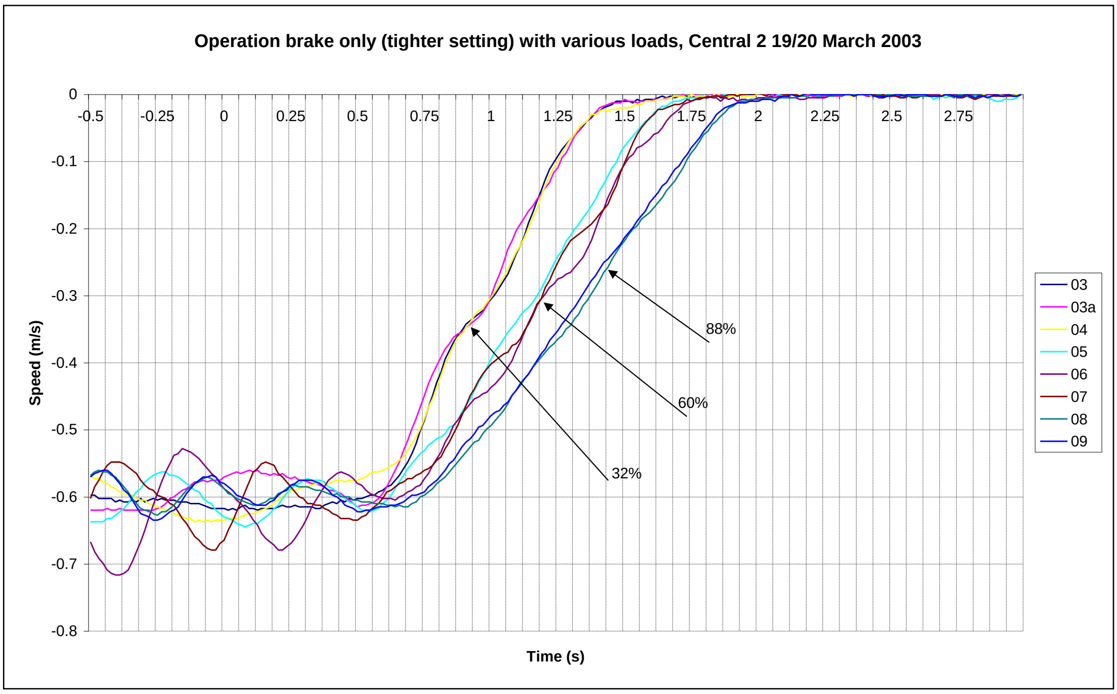

Figure 2 Weight test results for HDM10

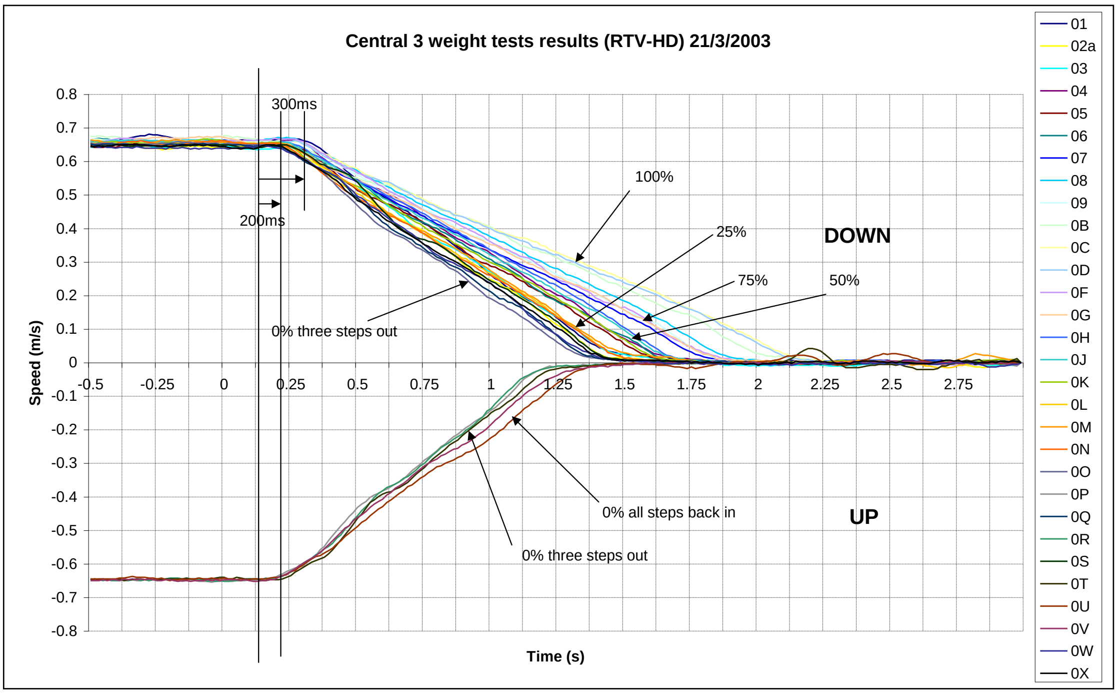

Figure 3 Weight test results for RTV-HD Type

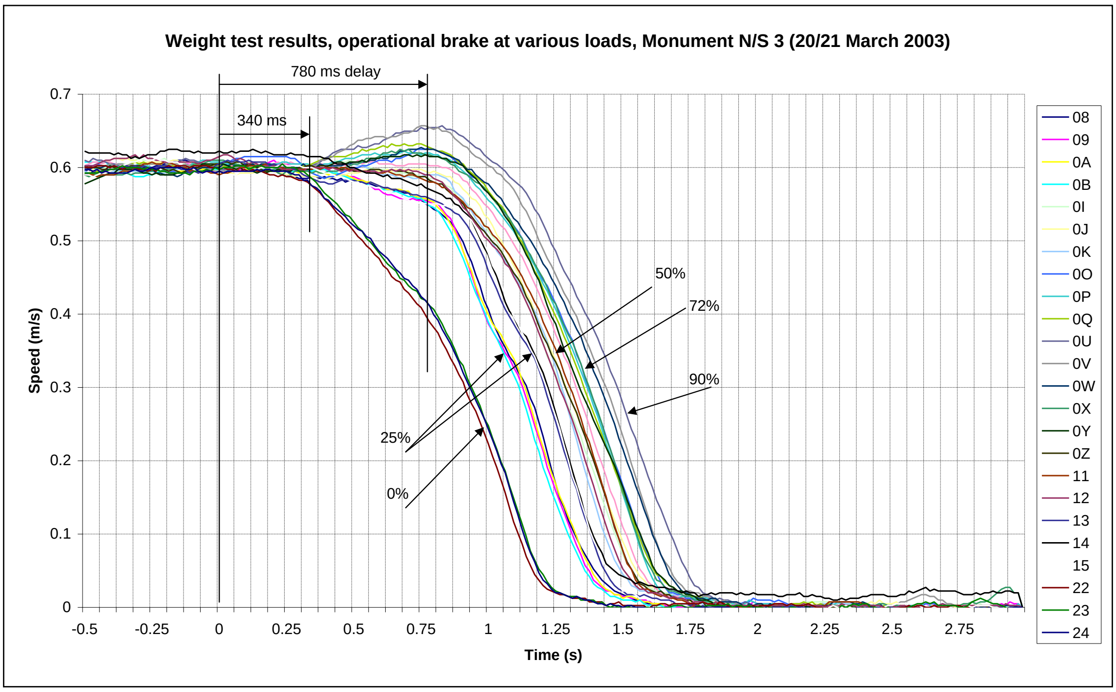

Figure 4 Weight test results for the HDMS Type

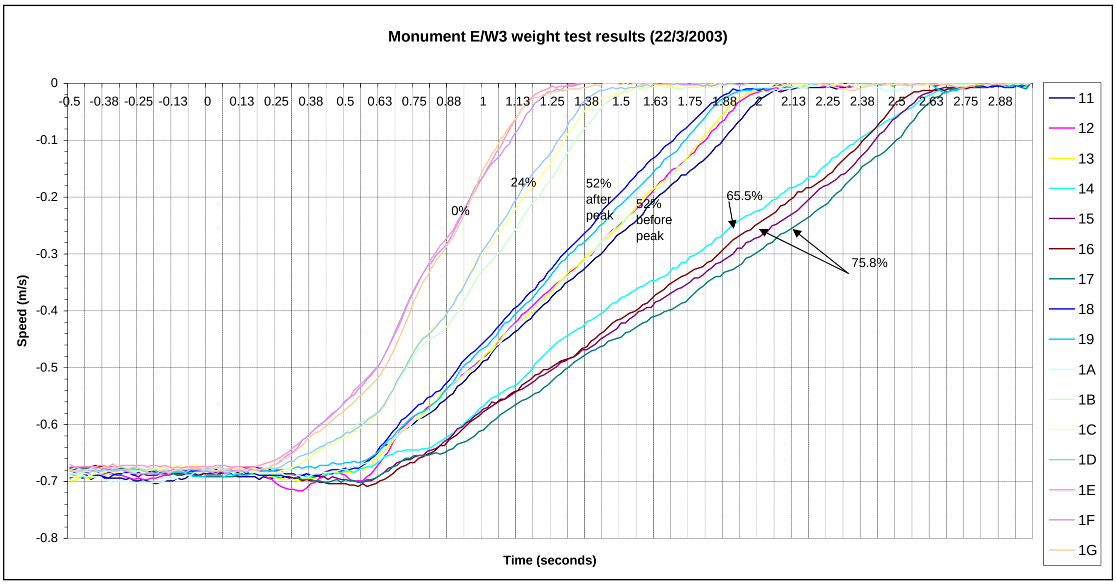

Figure 5 Weight tests results for the Compact Type

6 LIGHT SLIP TESTS AND ADJUSTMENTS

Based on the results from the weight tests, mathematical models were constructed for each of the four types of escalators. Then, light slip tests were then carried out on all other escalators. The operational brakes and the auxiliary brakes were adjusted on these escalators in order to achieve the required deceleration.

The philosophy of the light slip tests is based on isolating each brake and carrying out the tests on it separately to evaluate its efficiency. The light slip tests comprised the following tests:

1. Operational brake only: For this type of stop, the escalator is set up to stop under the influence of the operational brake. The controller must be set up such that it delays the application of the auxiliary brake long enough to ensure that the escalator has come to a full stop.
2. Auxiliary brake only: For this type of stop, the escalator is set up to stop under the influence of the auxiliary brake only. Usually, wiring is introduced into the controller to keep the operational brake lifted such that it does not contribute to the stopping braking performance. From a safety point of view, it is important to remember to remember any wiring that was introduced during the test.
3. Frictional stop: In a frictional stop, both brakes are kept lifted such that the escalator comes to rest under the influence of friction only.
4. Both brakes: Under this type of stop, both brakes are applied immediately and simultaneously (with any delay that is usually applied to the auxiliary brake bypassed).

A guidance table has been produced that can be used to adjust all the escalator during light slip tests. The guidance table is shown in Table 2 below.

Table 2 Table that shows the recommended values of deceleration under light slip tests

Three letter code	Escalator number	Rise (m)	Speed (m/s)	EN115 min. stopping distance as no load (mm)	EN115 max. stopping distance at full load down (mm)	min. no load stopping deceleration to prevent runaway (m/s^2)	min. no load stopping deceleration to comply with EN115 (m/s^2)	Ideal value of no load stopping deceleration (m/s^2)	Deceleration should not ever exceed (m/s^2)
AAA	1	7.830	0.60	267	1200	0.41	0.68	0.78	1.00
AAA	2	7.830	0.60	267	1200	0.41	0.68	0.78	1.00
AAA	3	5.950	0.75	350	1500	0.38	0.71	0.81	1.00
BBB	1	4.580	0.60	267	1200	0.34	0.61	0.71	1.00
BBB	2	4.580	0.60	267	1200	0.34	0.61	0.71	1.00
CCC	1	5.740	0.65	300	1300	0.37	0.66	0.76	1.00
CCC	2	5.740	0.65	300	1300	0.37	0.66	0.76	1.00
CCC	3	6.240	0.60	267	1200	0.38	0.65	0.75	1.00
CCC	4	6.240	0.60	267	1200	0.38	0.65	0.75	1.00
CCC	5	4.240	0.60	267	1200	0.33	0.60	0.70	1.00
CCC	6	4.240	0.60	267	1200	0.33	0.60	0.70	1.00
CCC	7	3.895	0.50	267	1000	0.32	0.54	0.64	1.00
DDD	1	17.920	0.60	267	1200	0.49	0.77	0.87	1.00
DDD	2	17.920	0.60	267	1200	0.49	0.77	0.87	1.00
EEE	1	5.070	0.60	267	1200	0.35	0.62	0.72	1.00
EEE	2	5.070	0.60	267	1200	0.35	0.62	0.72	1.00
FFF	1	6.400	0.60	267	1200	0.38	0.66	0.76	1.00
FFF	2	6.400	0.60	267	1200	0.38	0.66	0.76	1.00
GGG	1	15.644	0.60	267	1200	0.48	0.76	0.86	1.00
GGG	2	15.644	0.60	267	1200	0.48	0.76	0.86	1.00
GGG	3	15.644	0.60	267	1200	0.48	0.76	0.86	1.00
HHH	1	8.440	0.65	300	1300	0.42	0.71	0.81	1.00
HHH	2	8.440	0.65	300	1300	0.42	0.71	0.81	1.00
HHH	3	8.440	0.65	300	1300	0.42	0.71	0.81	1.00
III	1	8.148	0.65	300	1300	0.42	0.71	0.81	1.00
III	2	4.656	0.65	300	1300	0.34	0.63	0.73	1.00
III	3	3.492	0.65	300	1300	0.30	0.59	0.69	1.00
JJJ	1	4.580	0.60	267	1200	0.34	0.61	0.71	1.00
JJJ	2	4.580	0.60	267	1200	0.34	0.61	0.71	1.00
KKK	1	10.930	0.60	267	1200	0.45	0.72	0.82	1.00
KKK	2	10.930	0.60	267	1200	0.45	0.72	0.82	1.00
KKK	3	10.930	0.60	267	1200	0.45	0.72	0.82	1.00
KKK	4	10.930	0.60	267	1200	0.45	0.72	0.82	1.00

7 CONCLUSIONS

Due to the strict requirements of setting the escalator braking systems, it is necessary ensure that they are able to stop the fully loaded escalator running at rated speed within predefined distances. Traditionally, this has been done by using weights placed on the escalator steps and measuring the stopping distances.

A previous paper presented a mathematical model [12] that was developed for the Tyne & Wear Metro in order to allow testing to be carried on the escalator braking systems without the use of weights. A type test was carried out on each of the four types of escalators and mathematical models developed. Using the results from the mathematical model, recommended values for the deceleration under no load conditions were tabulated for each escalator on the network.

These recommended deceleration values have been compiled into a table that contains the maximum and minimum allowable deceleration values. The maximum limit ensure that the escalator stop is not too abrupt (and thus cause passenger falls). The minimum limit ensures that the escalator does stop within the stipulated distance (and thus comply with the requirements of the European standard EN115:2008).

A running test schedule for all escalators was then setup to ensure that every escalator has such a test carried out at least once a year (and adjusted accordingly if needed). Training was also carried out for the Metro staff on the method of measurement and adjustment.

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BIOGRAPHICAL DETAILS

Lutfi Al-Sharif is currently Professor of Building Transportation Systems at of the Department of Mechatronics Engineering, The University of Jordan. He received his Ph.D. in lift traffic analysis in 1992 from UMIST (Manchester, U.K.). He worked for 9 years for London Underground, London, United Kingdom in the area of lifts and escalators. He has over 20 papers published in peer reviewed journals the area of vertical transportation systems and is co-inventor of four patents and co-author of the 2nd edition of the Elevator Traffic Handbook. He is also a visiting professor at the University of Northampton (UK), member of the scientific committee of the annual Symposium on Lift & Escalator Technologies and a member of the editorial board of the journal Transportation Systems in Buildings.

Expert Systems for Lift Traffic Design

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Keywords: high-rise, lift, elevator, traffic analysis, calculation, simulation

Abstract. An expert system is software that emulates the decision-making ability of a human expert. Although software tools are available that automatically select a likely lift system, these designs should always be checked by an expert. This paper thus poses the question "What is required in order to develop a truly expert system for lift traffic design that encapsulates sufficient expertise for a well thought out and robust design?" The paper explores the synthesizing of the sufficient expertise of a lift traffic analysis expert and the implementation of this expertise into software. The knowledge base required, the design processes followed, and the subtleties applied when the human expert considers borderline cases are explored. The resulting "expert engine" can be used to produce software tools, or quick selection graphs and tables, based on the embodied expertise of the human expert, in order to answer specific traffic design questions within specified boundaries.

1 INTRODUCTION

An expert is a person who is very knowledgeable about or skillful in a particular area [1]. An expert system is computer software based on the expertise and problem-solving strategies of specialists in a particular field and designed to provide advice or solutions in that field [2].

An expert system is made up of a knowledge base and an inference engine [3]. These elements are obtained by interviewing expert(s). The information elicited is recorded as a rule set, typically using an "if-then" structure. The inference engine enables the expert system to draw deductions from the rules in the knowledge base.

This paper arises from an expert (Barney [4]) challenging the results of lift traffic planning graphs created by software for the draft ISO 8100-32. Lift traffic analysis and software experts (Peters, Dean) maintained that all that was needed was a complete rule set to reproduce any expert's design procedure in software.

Each time the expert challenges results generated by the software, new rules can be added to the expert system addressing the objection.

The result of this process provides an insight into the knowledge base required for an expert system for traffic design. The resulting expert engine can then be used to produce automatic lift selection software, selection graphs and tables.

An expert system is only as knowledgeable as the data sets and rules it is given. The expert system in this paper is based on the uppeak design procedure prepared for a discussion document [5]. The mathematics of the design procedure are discussed in CIBSE Guide D: 2015 [6]. The extensions to the basic procedure are not addressed, e.g. example multiple entrance floors, zones, double deck lifts, simulations, etc. all of which are within the human expert's area of expertise. Extending the expert system to cover all these areas is possible, but is not part of this paper.

2 DATA SETS AND RULES

2.1 Interval and handling capacity

Most design guidance documents require interpretation from an expert. For example, the required handling capacity for a residential building may be between 5 and 8% of building population per five minutes, and the interval required may be between 45 and 70 s [7] reflecting a range of expectations from “luxury” to “low income”. A solution achieving 5% handling capacity and 70 s interval will be very different from a solution achieving 8% handling capacity and 45 s interval.

For the expert system to offer a single solution, more specific criteria need to be specified, see Table 1. These values are used in the expert system developed for this paper.

Table 1 Handling capacity and interval design criteria from [5]

Building type	Required handling capacity (%POP) (persons/5-minutes)	Required lift installation interval (INT) (s)
Office	12	≤ 30
Hotel	12	≤ 40
Residential	6	≤ 60

Referring to CIBSE Guide D, this expert system developed for this paper will produce a solution which would be classified as “normal”. To extend the expert system to offer “luxury” and “low income” solutions, an additional user input of a building sub-type would be required, e.g. a drop-down combo box with the options “luxury”, “low income” and “normal”.

The human expert might consider a ≤ 60 s interval requirement a soft boundary and may for example, consider 61 s acceptable. The programmer must determine a hard limit. Barney asked for a tolerance of 10%., e.g. for residential buildings allow up to 66 s interval.

2.2 Rated load

A table of car sizes is required, with corresponding platform areas so that car loading can be determined, see Table 2.

Table 2 Rated load and platform area (source BS EN 81-20: 2014, Table 6)

Rated load (kg)	Maximum available car (platform) area (m^2)
450	1.30
630	1.66
800	2.00
1000	2.40
1275	2.95
1600	3.56
1800	3.92
2000	4.20
2500	5.00

Car selection assumes an average car loading of 80% of rated load is not exceeded where maximum car loading (persons) is determined assuming 0.21 m^2 per person in offices, 0.3 m^2 per person for hotels and residential buildings.

The above car selection methodology is appropriate in most countries. To extend the expert system to account for countries with a lower average body size, the expert system would require a drop-down combo box to select country.

Barney requested a 10% tolerance on car loading, so average loadings up to 82% will not be rejected (10% of (100-80) = 82%).

2.3 Door widths and passenger transfer times

A table of door widths is required so that passenger transfer and door operating times can be proposed, see Table 3.

Table 3 Door width and passenger transfer time for offices

Rated load (kg)	Door width (mm)	Single average passenger transfer (s)
450 – 800	800	1.2
1000	900	1.0
1275	1100	0.9
1600-2500	>1100	0.8

Table 3 is for offices. For hotel buildings 0.5 s is added to the passenger transfer time and 0.3 s is added for residential buildings.

2.4 Rated speed, acceleration and jerk

The preferred rated speed is calculated by dividing the lift travel by the nominal travel time as proposed in Table 4.

Table 4 Nominal travel time used in speed selection

Building type	Travel time (s)
Office	25
Hotel	25
Residential	30

The closest rated speed from the available rated speeds in Table 5 is selected, e.g. if the preferred rated speed is 2.3 m/s, then 2.5 m/s would be selected. Note the proposed values for acceleration and jerk based on experience [8].

Table 5

Rated speed (m/s)	Acceleration (m/s^2)	Jerk (m/s^3)
1.00	0.6	0.4
1.60	0.6	0.4
2.50	0.8	0.5
3.00	0.9	0.6
5.00	0.9	0.6
6.00	0.9	0.6

The flight times can then be calculated using kinematic equations [9]. A start delay of 0.5 s is assumed. Note: the tabulated acceleration and jerk values are lower than proposed in most design guidance documents following review of site measurements at a wide range of installations internationally [8].

2.5 Door opening and closing times

Door widths are selected from Table 3. Centre opening doors are selected for office and hotels, side opening doors are selected for residential. Based on these selections the door closing and opening times in Table 6 are assumed.

Table 6 Door closing and opening times

Door type	Closing (s)			Opening (s)		
Width (mm)	800	900	1100	800	900	1100
Side	3.0	3.3	4.0	2.5	2.7	3.0
Centre	2.0	2.3	3.0	2.0	2.2	2.5

A door pre-opening time of zero seconds (0 s) is assumed.

2.6 Number of lifts

The number of lifts is selected in the range one to eight. Larger groups are unusual and require special considerations which are not addressed by this expert system.

2.7 Number of floors

The number of floors above the main terminal is limited to 18 for office and hotels, and to 40 for residential buildings. This is because building zoning is not addressed by this expert system.

3 IMPLEMENTATION

The uppeak round trip time equations and their application are discussed in detail by Barney [6].

Implemented manually or using a spreadsheet, the human expert will calculate in five steps:

- A The total number of lift trips per five minutes required to achieve the interval, e.g. for a design criterion of 30 s interval, there will need to be 10 trips (300/10) per five minutes.
- B The required car size based on the required handling capacity and number of lift trips.
- C The round trip time based on the round trip time equations.
- D The number of lifts required to satisfy the interval criterion based on the calculated round trip.
- E If the resulting handling capacity is more than required, the car loading is reduced by a small amount iteratively, and round-trip time calculation repeated until the required handling capacity (also known as passenger demand) is equal to the calculated handling capacity.

The risk of implementing this approach in software is that a solution can be rejected unnecessarily at Step D. For example, if the number of lifts required is calculated as 4.05, five lifts would be selected by a software solving the requirement to select the minimum number of lifts which allow the configuration to satisfy the interval criterion. However, there is a strong possibility that if four lifts had been selected at Step D, after the iteration in Step E, the criterion would have been satisfied. The small increment over the integer value would be noticed and addressed by a human expert.

Thus, a different approach is needed in software. With software, the calculations are so fast that the round trip time of every possible number of lifts, rated load and rated speed may be considered, and the iterative process completed, without the possible rejection of a solution.

The expert system software starts with one 450kg car with a rated speed of 1.0 m/s and cycles up through the possible configurations until all criteria in Section 2 are satisfied. An alternative (probably faster) approach would be to use the HARint plane [10].

4 ADDITIONAL CONSIDERATIONS

When selecting lift installations, there are considerations in addition to traffic calculations [5], for example:

A An office building may require larger lifts to create a feeling of prestige, or to enable furniture and office partitions to be transported.
B A residential or hotel building may require larger lifts to accommodate furniture, stretchers and coffins.
C According to the operation of the building, there may be a requirement for separate goods lifts
D Where availability of lift service is crucial, a minimum of two lifts may be required despite a single lift meeting the criteria.

There may be other commercial, architectural, and occupant considerations.

These above considerations could be included in the expert system, but would require further questions to be asked of the user and assumptions built into the software by applying additional rules.

This expert system is designed only to select the minimum solution meeting the selection criteria in section 2, requiring an experienced practitioner to address considerations beyond the traffic calculation.

An expert practitioner might also consider a simulation of the selected solution.

5 APPLICATIONS

5.1 Expert system software

The expert system may be applied in local or on-line software. An example on-line interface is given in Figure 1. This example inputs for an 18 floor (above main entrance floor) building with a floor population of 60 persons, and an interfloor distance of 3.3 m.

The expert system reports the result: 6 lifts with rated load 1000 kg @ 2.5 m/s.

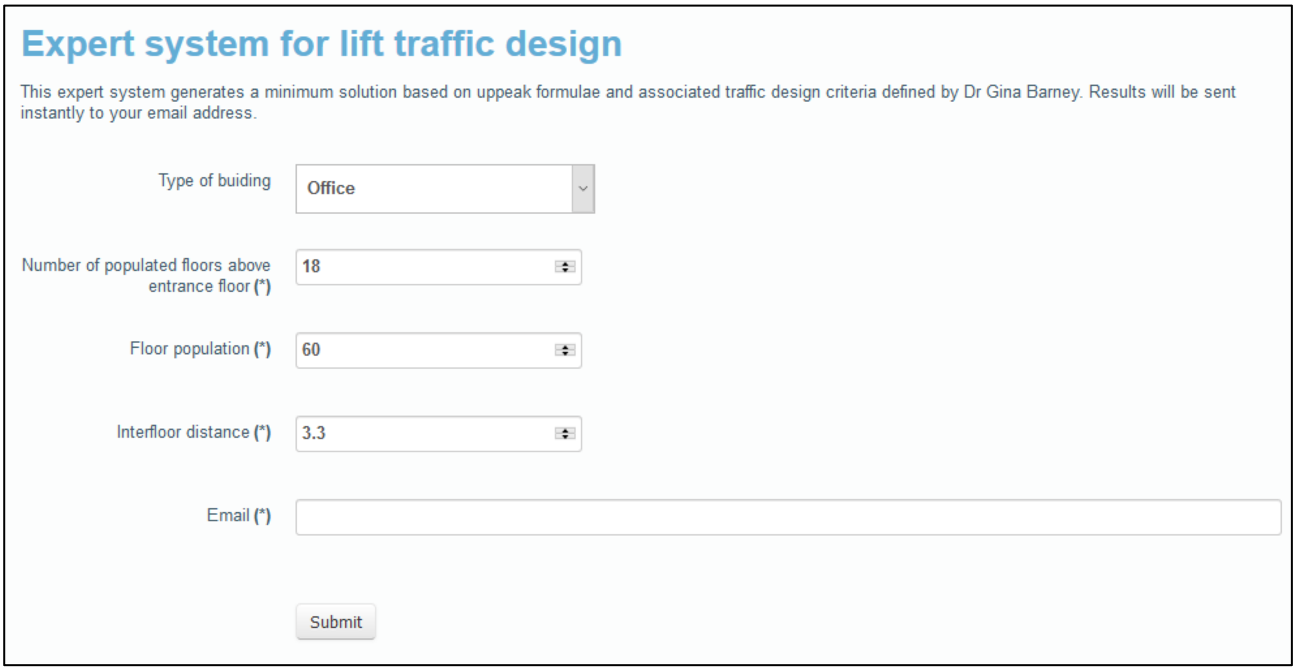

Figure 1 Example web interface to expert system

5.2 Tables and graphs

For an offline interface appropriate to printed design guidance documents, results can be presented in tabular or graphic form.

The tabular presentations in [5] are for:

A Office buildings up to 18 floors above the main terminal with interfloor heights 3.3 m, 3.6 m, 3.9 m and 4.2 m
B Hotel buildings up to 18 floors with interfloor heights 3.3 m, 3.6 m, 3.9 m and 4.2 m
C Residential buildings up to 40 floors with interfloor heights 2.5 m and 3.0 m

Figure 2 is an example for office buildings with interfloor distance 3.3 m generated by the expert system.

Note that for 18 floors above the entrance floor with a population of 100 persons per floor, the table reports "No solution meets criteria". This is because eight of the largest lift cars that were considered by the expert system do not meet the design criteria.

Barney [11] proposes a graphical representation of results, see Figure 3. This is similar in approach to Ruokokoski and Siikonen [4] in that the limit of a lift configuration is plotted against population and number of floors. Barney uses lines rather than shaded regions which is less cluttered when more configurations are being considered.

For example, suppose a lift installation is to be selected for an office building with eight floors above the entrance floor and a population of 2000 persons. The circled result shows that there is a choice of either 8 x 1800 kg (which is about right) or 8 x 2000 kg (which provides extra capacity) or 7 x 2500 kg (which requires less lifts). Lift speed selection is assumed to follow Section 2.4.

Table A.2a Lift installation selection table for office buildings (d_f=3.3 m)

Number of populated floors above entrance floor	Floor population									
	10	20	30	40	50	60	70	80	90	100
1	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s
2	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s
3	1 450 kg @ 1.0 m/s	1 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s
4	1 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s
5	1 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 630 kg @ 1.0 m/s
6	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 630 kg @ 1.0 m/s	3 800 kg @ 1.0 m/s	4 630 kg @ 1.0 m/s
7	2 450 kg @ 1.0 m/s	2 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 630 kg @ 1.0 m/s	4 450 kg @ 1.0 m/s	4 630 kg @ 1.0 m/s	4 630 kg @ 1.0 m/s	4 800 kg @ 1.0 m/s
8	2 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 630 kg @ 1.0 m/s	4 450 kg @ 1.0 m/s	4 630 kg @ 1.0 m/s	4 800 kg @ 1.0 m/s	4 1000 kg @ 1.0 m/s	5 800 kg @ 1.0 m/s
9	2 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	3 450 kg @ 1.0 m/s	4 450 kg @ 1.0 m/s	4 450 kg @ 1.0 m/s	4 630 kg @ 1.0 m/s	4 1000 kg @ 1.0 m/s	5 800 kg @ 1.0 m/s	5 1000 kg @ 1.0 m/s	5 1275 kg @ 1.0 m/s
10	2 450 kg @ 1.6 m/s	3 450 kg @ 1.6 m/s	3 450 kg @ 1.6 m/s	3 630 kg @ 1.6 m/s	4 450 kg @ 1.6 m/s	4 630 kg @ 1.6 m/s	4 1000 kg @ 1.6 m/s	5 800 kg @ 1.6 m/s	5 1000 kg @ 1.6 m/s	5 1600 kg @ 1.6 m/s
11	2 450 kg @ 1.6 m/s	3 450 kg @ 1.6 m/s	3 450 kg @ 1.6 m/s	4 450 kg @ 1.6 m/s	4 630 kg @ 1.6 m/s	4 1000 kg @ 1.6 m/s	5 800 kg @ 1.6 m/s	5 1275 kg @ 1.6 m/s	5 1600 kg @ 1.6 m/s	5 1800 kg @ 1.6 m/s
12	2 450 kg @ 1.6 m/s	3 450 kg @ 1.6 m/s	4 450 kg @ 1.6 m/s	4 450 kg @ 1.6 m/s	4 800 kg @ 1.6 m/s	5 800 kg @ 1.6 m/s	5 1000 kg @ 1.6 m/s	5 1600 kg @ 1.6 m/s	6 1275 kg @ 1.6 m/s	6 1600 kg @ 1.6 m/s
13	2 450 kg @ 1.6 m/s	3 450 kg @ 1.6 m/s	4 450 kg @ 1.6 m/s	4 630 kg @ 1.6 m/s	5 630 kg @ 1.6 m/s	5 1000 kg @ 1.6 m/s	5 1600 kg @ 1.6 m/s	6 1275 kg @ 1.6 m/s	6 1600 kg @ 1.6 m/s	6 2500 kg @ 1.6 m/s
14	3 450 kg @ 1.6 m/s	3 450 kg @ 1.6 m/s	4 450 kg @ 1.6 m/s	4 800 kg @ 1.6 m/s	5 800 kg @ 1.6 m/s	5 1600 kg @ 1.6 m/s	6 1275 kg @ 1.6 m/s	6 1600 kg @ 1.6 m/s	6 2500 kg @ 1.6 m/s	7 2000 kg @ 1.6 m/s
15	2 450 kg @ 2.5 m/s	3 450 kg @ 2.5 m/s	4 450 kg @ 2.5 m/s	4 800 kg @ 2.5 m/s	5 800 kg @ 2.5 m/s	5 1275 kg @ 2.5 m/s	6 1275 kg @ 2.5 m/s	6 1600 kg @ 2.5 m/s	6 2500 kg @ 2.5 m/s	7 2000 kg @ 2.5 m/s
16	2 450 kg @ 2.5 m/s	3 450 kg @ 2.5 m/s	4 450 kg @ 2.5 m/s	4 1000 kg @ 2.5 m/s	5 1000 kg @ 2.5 m/s	6 1000 kg @ 2.5 m/s	6 1600 kg @ 2.5 m/s	6 2000 kg @ 2.5 m/s	7 1800 kg @ 2.5 m/s	7 2500 kg @ 2.5 m/s
17	3 450 kg @ 2.5 m/s	3 450 kg @ 2.5 m/s	4 630 kg @ 2.5 m/s	5 630 kg @ 2.5 m/s	5 1275 kg @ 2.5 m/s	6 1275 kg @ 2.5 m/s	6 1800 kg @ 2.5 m/s	7 1800 kg @ 2.5 m/s	7 2500 kg @ 2.5 m/s	8 2500 kg @ 2.5 m/s
18	3 450 kg @ 2.5 m/s	4 450 kg @ 2.5 m/s	4 630 kg @ 2.5 m/s	5 800 kg @ 2.5 m/s	6 1000 kg @ 2.5 m/s	6 1600 kg @ 2.5 m/s	7 1600 kg @ 2.5 m/s	7 2500 kg @ 2.5 m/s	8 2000 kg @ 2.5 m/s	No solution meets criteria

Notation 5 1275 means 5 lifts with rated load 1275 kg.

Figure 2 Example tabular presentation of results for expert system from [5]

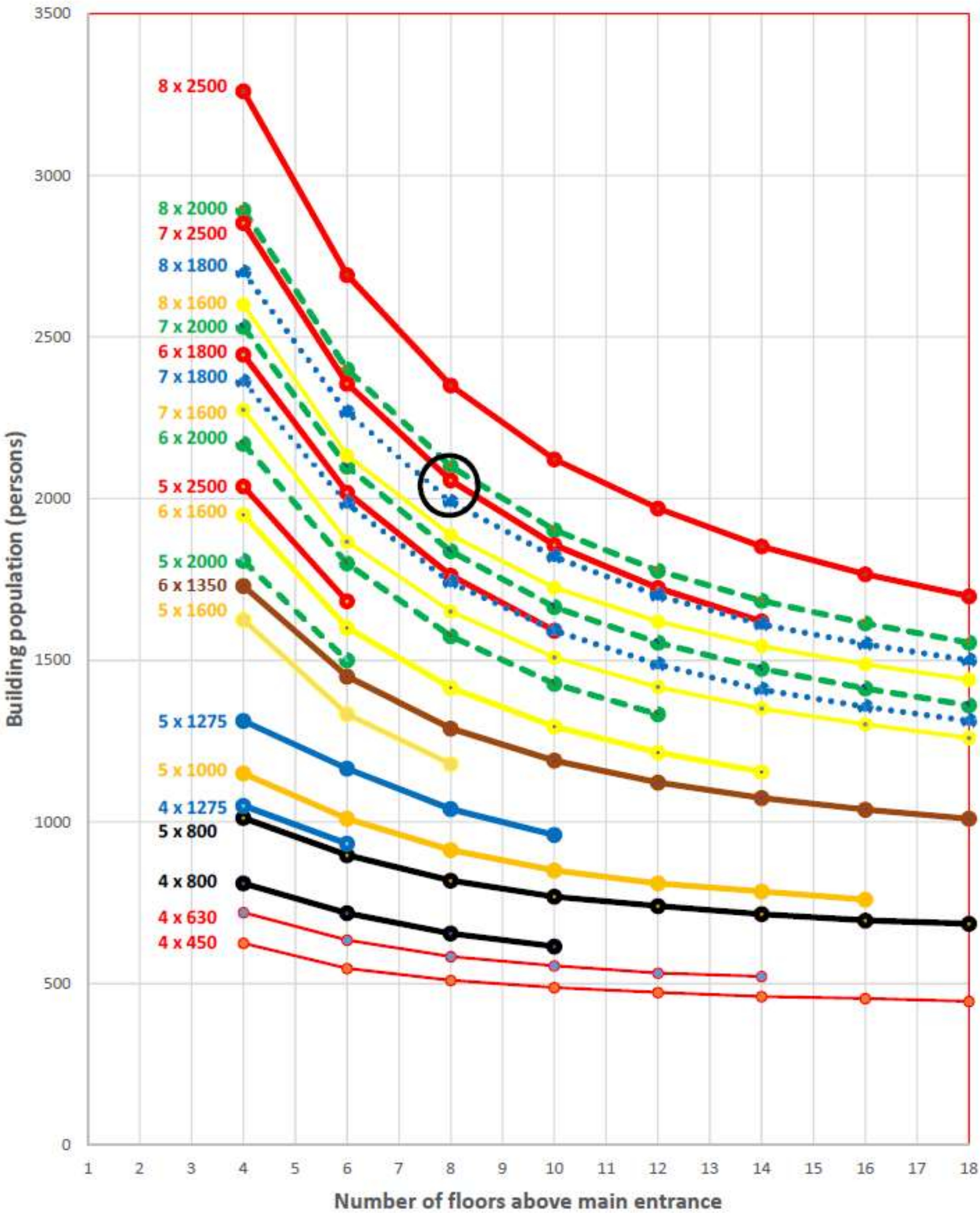

Figure 3 Example graphical presentation of expert system results proposed by Barney [11]

6 CONCLUSIONS

Expert systems for lift traffic design are feasible, but they are only as knowledgeable and as expert as the rules and data sets on which they are based.

The creation of charts and tables for quick selection has a long history [12]. Over the years many charts, tables and software algorithms have been produced, of varying provenance and transparency.

In this paper the authors have introduced and described an expert system implementing the uppeak design procedure applying data sets and rules provided by a respected expert. The flexibility of the expert on some design parameters has been expressed with a tolerance; an alternative to investigate in the future is the application of fuzzy rules [13].

Limitations of the expert system and how it could be extended have been discussed. Given this foundation, expanding the expert system for more complex scenarios and other analysis techniques, including simulation can be added.

De-skilling engineers by developing expert systems has technical risks. In the foreseeable future, not every scenario or exception will be anticipated by software developers and the human experts they consult. Thus, transparency of the data set and rules applied by any expert system for lift traffic design need to be reviewed and understood by an experienced practitioner before the results are applied.

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Goods Lifts. Who Needs Them?

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Abstract. Much has been written about the importance of passenger lifts, their performance and passenger traffic analysis in office and residential buildings over many years. The same cannot be said of goods lifts, even though they play a vital role in the efficient running of buildings. The movement of goods, plant, furniture, and the needs of the emergency services, all need to be considered when assessing the services necessary to ensure the smooth back of house operations that contribute to well managed buildings and satisfied tenants.

The move to higher population densities in office buildings combined with introduction of magnet attractions such as roof top restaurants and retail outlets brings to light the need to reassess both the role of the goods lift and how goods lift provision is assessed. Goods lifts are a key part of building logistics and failure to meet the needs of tenants and owners can be both expensive and frustrating. The humble goods lift provides a wide range of services from everyday deliveries and the movement of back of house personnel to enabling fit out and refurbishment works to be undertaken whilst minimising the impact on passenger lift usage.

Recent years has seen the growth in public access to major landmark buildings with restaurants, retail outlets and viewing areas being located within and at the tops of tall buildings. This together with higher office density levels brings new meaning to planning building logistics and the need for correlation between loading bay and delivery capacities and the ability to distribute goods and materials efficiently and quickly up the building. In addition, the removal of waste is a key use of goods lift time and the ability to manage this aspect of building operations should form a key part of the design associated with goods lift use and building logistics.

The management and operation of goods lifts is something largely overlooked in building design and yet the poor provision of such services has a significant impact on both building operations and tenant satisfaction.

This paper looks at the changing operational needs of office buildings. The current guidance provided, and the key points of reference are examined and assessed against todays demanding requirements for efficient management of modern buildings.

1 INTRODUCTION

This paper seeks to examine how the provision of dedicated goods lifts in office buildings is currently determined and whether this approach is still appropriate to today’s buildings operational requirements.

The paper does not seek to examine the costs associated with the various types of goods lifts or their compliance to the various EN suite of standards such as EN81-70. The prime purpose of the paper is to look at the changes that have, and are taking place, and to compare current guidance to today’s demands.

The use of goods lifts is reviewed both during the building construction phase (beneficial use) and afterwards in normal operation. It is suggested the design criteria should come from analysing the possible uses of the lifts and what they are required to accommodate, both in terms of load (weight) and volume. In addition, the operational use of the lifts and their ability to provide an efficient and flexible means of goods and material distribution, as part of a coordinated approach to building operational logistics, is also considered.

Dedicated goods lifts provide an essential service and are the ‘life blood’ of office buildings. Although mainly back of house and unseen by most tenants their ability to service the building is a major part of the building’s operation. The need for a wider assessed provision of sufficient lifts of suitable capacity, speed and flexibility fundamentally changes the way in which goods lifts provision is perceived and established.

The examples covered in the paper focus on larger office buildings but are equally applicable to smaller offices where facilities such as loading bays and dedicated goods receiving areas provide a means of managing the flow of inward goods and outgoing waste.

In this paper the term ‘goods lift’ refers to ‘goods passenger lifts’ in all instances and does not refer to goods only lifts that are none people carrying.

2 AREAS OF FOCUS

The key areas of focus move us away from looking at goods lifts in isolation to looking at the wider aspects of building operations and logistics upstream of the lifts themselves.

For example, loading bay design, capacity and management, storage areas, vehicle delivery schedules and means of moving goods within the building all impact on the design of goods lifts and are major considerations within a coordinated approach to the management of building logistics.

The changes to waste management, in consideration of environmental impact, have led to the ‘steaming’ of waste. This now means waste is separated at source and each stream has its own containment and storage requirements both on office floors and at the consolidation point, generally the building loading bay.

Changes in the use of buildings and public access to ‘magnet attractions’ such as roof top restaurants, viewing galleries, retail outlets and tenant amenity spaces all impact on the ability of the goods lifts to service the building. The trend by developers to look to provide roof top amenity spaces is a more recent phenomenon. These are all important areas that need to be serviced and should form part of the thinking when considering goods lift provision.

3 WHAT HAS CHANGED?

Within office building design probably the single biggest change is a move to greater occupational density. The change from cellular to open plan offices combined with a need for offices to ‘earn their keep’ has led directly to higher occupational densities as organisations seek to minimise their costs and consolidate their operations. As a result, developer’s now design for higher density levels in a bid to attract tenants

The change in planning requirements and the desire for the buildings to encompass the public realm, the rise of ‘magnet attractions’, together with developers seeking to provide better facilities, such as roof top amenity spaces, has introduced the need to services these areas both for people and goods.

The result is higher levels of services for such facilities needing to be provided while maintaining good service to the remainder of the building.

Also significant is the change in delivery methods and systems. The introduction of manual handing regulations has led to the greater use of lifting aides, palletised goods and wheeled caged trollies as opposed to manhandling heavy loose packaged items or the use of sack barrows.

The reduction in postal deliveries is countered by the rise in deliveries by courier. These have progressed from motor cycle deliveries of small packages to large items delivered by vans and small lorries. The rise of ad hoc, same or next day deliveries and the 'long hour' culture of modern delivery services bring new challenges in building operations and management. The ability to track deliveries raises expectations that goods will be received on time and distributed quickly. This shift in dynamics requires a more flexible response from that of the past. The ability to meet the changing needs, expectations and demands of tenants makes the management of building logistics far more important, requiring a coordinated approach.

Another significant change has been in environmental standards on issues such as the separation and recycling of waste. This has led directly to differences in the way waste is managed. The need for different containers for different waste streams adds to the storage requirements on floors and in loading bays, and while not perhaps significant in terms of weight the number of containers to be moved puts added pressure on the goods lifts in terms of the number of journeys needed to service the demand.

The use of goods lifts during the construction of the building has always been a major consideration in the planning of construction logistics. However, there are now wider considerations in this approach as the goods lift become an integral part of planning how buildings get built. The greater use of 'jump lifts' is testament to the changes in building techniques which are only set to put greater emphasis on seeing the goods lift as a 'tool' in the building process.

4 WHAT ARE GOODS LIFTS USED FOR?

Initially it is probable the goods lifts will be used to aid the construction of the building. While passenger lifts may also be used in this fashion these are generally dedicated to the movement of people and smaller items such as tools.

The early use of lifts, particularly the goods lifts, brings major benefits to the construction process allowing for the removal of builder's hoists, the closing of the building façade and with that the ability to make the building water tight. The goods lifts have in many instances a greater capacity and speed than the builder's hoists, meaning people, equipment and materials can be moved faster. Thus, they can be significant factor in the construction logistic plan as the building works progress. However, should the goods lift provided be insufficient to service the construction phase of the works then significant costs can be incurred together with prolonged programmes brought about by the inefficiencies of retaining the external hoists and late closing of the building.

The capacity, size and number of goods lifts are factored into the logistics planning of both the construction completion and the following fitout works. The need to accommodate large pieces of plant and equipment together with fit out materials and furniture, as tenants take occupation, forms a key part of the logistics planning. Together with the material sizes, consideration needs be given to the size and weight of the protective packaging and the means of moving the materials. All of these are major consideration in the goods lift design.

While having been in existence for well over 30 years the use of the 'jump lift' is increasingly applied to high rise buildings as a means of bringing the benefits of the permanent capacity, with perhaps slightly lower speeds, to the building process and serves to emphasise the importance of early beneficial use lifts in the building process.

It is important to remember that every lift that enters beneficial use must be fully compliant with the Lift Regulations and CE marked. Following the beneficial use period, the lifts are generally fully refurbished and retested before being finally handed over for client and public use.

Once the building is completed and operational the goods lifts fulfil several roles, mainly divided into the daily inward and outward movement of goods and materials. The inward movement of consumable office materials, electrical items, maintenance equipment, chemicals, postal/courier deliveries, food and building fit out materials, etc. are required. As is the outward movement of general office waste and equipment, food waste, redundant fit out material, empty delivery trollies and bins.

The use of the goods lifts by ‘back of house’ staff to move around the building is a key part of the functioning of the building and needs to be facilitated. This can include the distribution and collection of post as well as courier deliveries or collections.

In addition, plant replacement strategy is a key part, albeit not a very regular one, in which the goods lift plays a vital role. The ability to carry both the heaviest and largest items of plant form part of the usage required. In some instances, a ‘special’ service is required, where the load to be carried exceeds the capacity of the lift. The additional load requirement will depend on the circumstances but an increased capacity of between 15-25% of the rated load is not uncommon.

Increasingly there is a tendency to use good lifts to move exterior glass panels, which due to the design of the façade or limited capacity of the Building Maintenance Unit (BMU), cannot be taken up the outside of the building. In these circumstances the goods lifts form part of the façade maintenance strategy and need to accommodate the building exterior glazing panels.

Use by the emergency services is also a consideration. While not recommended in British Standard (BS) 9999:2017 [1] it is highly likely that the goods lift will be the only lift of sufficient size in the building to fulfil such a function. The ability to accommodate stretchers to move injured people is a necessity that is largely overlooked in design and only becomes apparent when the service is needed, but not available. Stretcher sizes are increasing as the amount of medical aids attached increases. The ability to accommodate this important requirement is essential and needs to be factored into the sizing of door widths and car depth if the goods lift is the only means of moving injured people in such a way.

The transportation of dangerous or hazardous materials is mostly associated with toxic or contaminated substances. However, other materials can fall into these categories such as general cleaning materials, water conditioning salts, glass, materials with high dust content, anti-corrosion liquids for water systems and food waste. Although these are not necessarily heavy the need to transport such materials may require special arrangements involving goods lifts.

5 HOW DO GOODS COME INTO AN OFFICE BUILDING?

Most modern office buildings have loading bays either at ground or basement levels. Access to the loading bays for commercial vehicles can be via a ramp or, where space is limited, by vehicle lifts.

Loading bays by design can accommodate anything from cars and small vans to articulated lorries. Most day to day deliveries, especially in inner city locations, are by smaller vehicles up to 7 tons but can be up to ‘large truck’ size (circa 20 tons). The use of vehicle lifts will pose a restriction on the size and weight of vehicles, but, generally accommodating dedicated waste removal vehicles is a criterion in the design of the lifts. The use of vehicle lifts also requires a more stringent management of the loading bay logistics. With finite loading bay capacity additional vehicles must be held at street level if there is any turn-around time delay or the vehicle lifts are out of service. This is a major problem in congested city centres and effectively means the operation of the loading bay, and the operational logistic of the building are contingent on both the reliability of the lifts and the efficiency of the loading bay operation itself.

Goods are generally transported either loosely packed or preloaded onto wheeled cages, pallets or small trollies. The trend to palletised packing brings considerable benefits in terms of consolidation and material/manual handling as they are generally moved by fork lift or ‘pump up’ truck. Examples are shown in Appendix A.

To effectively manage the loading bay logistics deliveries are ‘booked’ in advance and sometimes held at a marshalling location a little way from the building before being called forward to be unloaded. Verification of the delivery is generally sought with the tenant/customer before being distributed to the relative floor. This distribution can either be by the delivery company or the customer collecting the goods at the loading bay. In both instances it is the goods lift that will provide access to and from the loading bay.

As part of the loading bay design, short periods of storage for both inwards and outward movement of goods or waste is required. It must accommodate wheeled cages, pallets and separated waste containers all of which adds to the logistics of the loading bay operation.

Most large office buildings also have a ‘courier’ and mail room where smaller deliveries, that arrive on an ad hoc basis are received, and from which they are distributed via the goods lifts to their destination

6 GOODS MANAGEMENT STRATEGIES WITHIN OFFICE BUILDINGS

Many large buildings operate 24 hours a day 7 days a week. Some businesses operate 24/7 and if not, cleaning, maintenance and refurbishment works are often undertaken out of business hours, at nights and at weekends.

General office deliveries of are mostly between 6.00am and 10.00pm while office cleaning and waste removal are between 7.00pm and midnight. If the building has a public restaurant, then goods lifts will need to be available until the early hours to restock, remove food waste, clean and provide access for staff.

To effectively manage the loading bay and maximise the use of the goods lifts it may be necessary to coordinate the vehicle delivery booking system with a goods lifts booking system. This ensures unloading of the vehicles is aligned with the quick distribution of the goods to their destination. Lifts are taken out of service and switched to independent/priority control and driven from within the car to move the goods from the loading bay to their destination floor providing the most effective and efficient use of the loading bay and goods lift resources. Set time ‘slots’ are allocated during the day for this type of delivery and distribution arrangement. The timing of these slots is dependent on the approach taken by the loading bay manager, but it does provide knowledge to goods lifts users as to when lifts are ‘free running’ and available and when service may be restricted/limited.

By example, a 1m sq. ft (circa 93,000m^2) office building [2] has an average of 536 deliveries/collection recorded per week based on a 6-day week, some 89 each day. Over a 16-hour day this equates to an average of one delivery every 10/11 minutes during the day, but with greater frequency during working hours this can reach see vehicles arriving every 6/7 minutes.

For buildings that only operate during business hours the need for tight logistics management is potentially greater. Depending on the location, function and use of the building there may be less flexibility to deal with all the building’s needs. If this is the case, it is possible the provision of goods lifts should be greater.

Regardless of building opening hours it is almost certain that the need to operate goods lifts will exceed office hours. The recognition and provision of this forms part of the overall successful strategic approach to logistics management.

7 BUILDINGS WITH PUBLIC ACCESS FACILITIES

Other facilities the building may offer also need careful consideration. Public access spaces that have restaurants, retail outlets and viewing areas all need to be serviced to varying degrees.

Public restaurants in the upper parts of buildings, especially at roof level, require a dedicated goods lift service. Generally, these types of facilities have long opening hours. In a few cases the restaurants can be open 24 hours a day.

The levels of services required in such circumstances are considerable and it is not always fully appreciated that while separate provision is made for public access to these areas the same is not the case for the movement of goods.

Restaurants, in particular, have significant servicing needs, not simply food in and waste out. Other service provision includes the movement of:

- Restaurant staff
- Cleaners and cleaning materials
- Drinks and beverages.
- Disposal of separated waste
- Laundry
- Cooking oils and condiments
- Furniture
- Special function requirements.

Spillages from fresh food containers are common. Smells are a significant problem, especially related to the carrying of fresh meats and fish and the removal of food waste. In many instances these issues are not appreciated or considered, either in the operation of the building, or the design of the lift car interiors.

When considering the recent issues experienced at several tall buildings with roof top restaurants the lack of a dedicated goods lift is a significant problem. This has resulted in one of the goods lifts provided for general use being effectively taken over to service the restaurants, to the detriment of goods service to the remainder of the building.

Retails outlets and small coffee shops at high level in the building also merit special consideration. The service need of these types of outlets may not be as intense as restaurants but the ability to provide a satisfactory service is just as important.

8 BUILDING DESIGN FOR GOODS LIFTS

While the design of the goods lift itself is important the environment in which it operates, and the building interfaces are of equal importance. Sufficient space in front of the lifts and in the goods lift lobbies is essential. The ability to accommodate the storage of trollies, bins and stacked boxes/bags is necessary if these are not to be left in tenant spaces. This is especially important where restaurants and food outlets are concerned. Spillages or leakage from food/beverage containers and smells are things to be considered and are obviously things to be avoided in public or office areas.

The configuration of two or more goods lifts is also an important factor. Ideally, they should be arranged to be next to each other facing into a common lobby. The ‘L’ shaped arrangement should be avoided unless the lobby is of sufficient size to accommodate the required off floor storage.

Where more than one goods lift is provided they should operate as a group and not be distributed within separate cores. This arrangement leads to inefficiencies in both the service and use of the lifts.

Where lifts do not have lobbies on the floors it has to be accepted that temporary storage of goods and possibly food will be in view of the tenants and that office space will need to be sacrificed to accommodate stored items. This could also mean potentially flammable waste is stored on floors adding to the fire risk and will need consideration as part of the fire strategy. It is also important that stored materials do not obstruct fire exits.

Where goods lifts do open directly into tenant space the need for robust finishes is a consideration. The walls and floors areas, around the front of the lifts, are prone to damage from trollies, pallet trucks and bins. Floors are susceptible to damage from high point loadings of wheels and it is essential that the design of the floor in front of the goods lifts is suitable for the loads likely to be imposed. Raised flooring and carpet are not as robust as concrete floor finishes found in many goods lift lobbies.

At the loading bay level, and possibly other floors where dedicated goods lift lobbies are provided, the cleaning regime may include the areas being hosed down and scrubbed. In these situations, consideration should be given to raising the landing entrance sill 25mm (similar to firefighting lifts) to prevent water ingress into the shaft.

Where the lift entrance is fitted with a full depth architrave the inside landing edge of the architrave should be reinforced to a height of between 1.0 and 1.2m from floor level and robust architrave fixings provided. This area is subject to damage as goods are move into and out of the lifts and will soon show the effects of a poorly designed architrave arrangement.

Finally, from a maintenance perspective the finishes to the landing doors and architraves needs careful consideration. The use of stainless steel is attractive but once damaged is unforgiving in terms of repair, it generally means the door or architrave needs to be replaced. This is expensive and in the case of architraves is not always practical. This leaves few options but ‘skinning’ the architrave is one, albeit not necessarily an easy solution.

Painted doors and architraves provide a practical solution and can be filled and sprayed easily if damaged.

9 ESTABLISHING THE CAPACITY OF GOODS LIFTS

Goods lifts come in an array of capacities and configurations and both ISO 4190 [3] and BS-EN-81-20 [4] provide guidance. However, some types of goods lifts have limitations. Machine room less (MRL) goods lifts for example generally have a maximum capacity of 3000kg and are limited to speeds of circa 1.6m/s. ‘Traditional’ goods lifts, those with a machine room, however are capable of both higher capacities and speeds. Guidance provided in the British Council of Offices (BCO) 2015 [5] edition recommends that goods lift should be capable of travelling from the loading bay to the top floor served in 60 seconds.

While recognising any limitations the starting point should be in determining if the lift is to be used for plant replacement. The need to accommodate heavy or large items of plant is vital to the plant replacement strategy and this requirement is key in establishing both the load capacity and size of the lifts. It generally transpires that the heaviest piece of plant is not necessarily the biggest, so while the heaviest is to be accommodated, the need to cater for large, but lighter, items will inform the height and depth of the car. As we know floor area determines the capacity of lifts and it may be that the need to carry large but light items increased the platform area and hence the capacity.

One area that has not been considered greatly in the past is the ability to replace trees and large plants. These are becoming more popular in office atriums, terraces and roof gardens and are often overlooked, especially if the original installation was accomplished using the site crane during construction.

The next criterion is the ability to move building fit out materials. One consideration here is the building floor to floor height. This is likely to determine the length of fit out materials such as dry lining boards (standard lengths of up to 3.3m), glass partitioning, door and door frame heights. While lighter than anything required for plant replacement they are generally longer. Packaging and the means of transportation also needs to be considered as part of the assessment.

The next consideration is the use of the goods lift during construction. This is usually required, and items such as scaffold equipment, piping, valve units, electrical switch gear, large cable reels, temporary protective screening, and other construction materials needs to be considered.

The use of pallets during construct and fit out together with the extensive use of Eurobins for waste removal, should also form part of the assessment. The ability to fit both the large standard 1200m x 1000mm pallets and the 1240mm x 1070mm 1100 litre Eurobins efficiently into the car makes for a far more efficient use of the goods lifts both during construction and in the general long-term operation of the building.

While car length and width are a major factor, the car height is equally important. The ability to stand and stack materials vertically allows for a more efficient means of transporting goods. Car heights of up to 3.5m allows better service during construction and for the subsequent fit out works during the life of the building.

The provision of ‘top hats’ on the car roof is also something to be considered. This is very much dependent type of lift, the depth of the car and the roping arrangement. While many MRL lifts have underslung cars, traditional goods lifts may have sheaves mounted on the car top. With some traditional 2:1 roping arrangements the position of the car top sheaves and supporting steelwork may limit both the possibility of fitting a top hat and its size. In addition, the safety issues related to accessing a higher level at the rear of the car top for maintenance personnel may mean it does not provide the solution intended.

Along with the car size and height comes the need for wide, tall lift entrances. Doors 1400-1600mm wide x 2400 - 2700mm high will accommodate items such as pallets, Eurobins, and wheeled trollies. Stillages, wheeled high sided trollies, used for the movement of glass, plasterboard and large flat items will also be accommodated within these entrance sizes. Providing large entrances also gives flexibility and is an efficient means of loading lifts quickly.

The assessment of service needs during construction and the on-going operation of the building should form the basis of the goods lifts size and capacity. Without this the risk is the goods lift provided will be inadequate for the building’s needs leading to an ‘operationally sick’ development that will never be right. This detracts from the ability to let/sell the building and hence reduces its attractiveness to potential tenants/buyers.

10 ESTABLISHING THE NUMBER OF GOODS LIFTS REQUIRED.

To establish the number of goods lifts required the starting point is to look at existing guidance.

The 2015 edition of Chartered Institute of Building Services Engineers (CIBSE) Guide D [6] provides a means of establishing the number of goods lifts in office buildings and is based on a calculation of the floor area.

For usable floor areas up to 10,000 m² one lift

For each additional 20,000 m² one additional lift.

The load capacity of lifts is detailed as a minimum of 1600kg with consideration of lifts up to 2500kg.

It is understood this criterion is mainly based on experience and has been in existence for some considerable time.

From the authors research there is no other formally published criterion that is used to formulate the number of lifts required although reference to goods lifts, their operation and use are covered in many books and articles published over a number of years.

BS5655 Pt 6 [7] covers the design and use of goods lifts but does not consider the wider management of logistics in buildings or the means of establishing the number of lifts required

11 POINTS OF REFERENCE RELATED TO WASTE MANAGEMENT.

In terms of waste management BS 5906 (2005) [8], provides guidance on waste management from a wide variety of different buildings and covers a comprehensive spectrum of waste types, many of which are not particularly associated with offices.

Interestingly the guidance details waste in terms of volume as opposed to weight.

Table 1 of the standard [8] provides information on the volumes of waste created in various types of buildings including offices. For offices the stated waste generated is 50 litres per person per week. Some quick calculations will soon establish the volume for a large office building and we will see an example of this below.

12 BUILDING WASTE GENERATION

12.1 Establishing the building population

To arrive at the levels of waste generated in office buildings, using BS5906 [8] guidance, it is first necessary to establish the building population. The population is derived from a density factor, whereby each person is allocating an area measured in square metres. This is expressed as a ratio such as 1:14 or 1:10, meaning one person to every 14 or 10 square metres of occupiable space.

The space available for occupation is generally referred to as the ‘net internal area’ (NIA). The term ‘utilisation’ is used in association with the NIA and is derived from the total floor area (NIA) less the floor space used for circulation, storage and office facilities (meeting spaces, kitchens, photocopiers, etc.). For most offices the utilisation factor is 80% meaning 20% of the floor area is not occupied.

Population densities in offices have increased sharply over recent years from 1:14 some 15-20 years ago to 1:10 or commonly 1:8 today. Some high-density areas such as trading floors are occupied at 1:6.

12.2 Waste generation

If the criterion in CIBSE Guide D [6] is used as a starting point then the provision of a single goods lift is in theory suitable for a building of between 10,000m² and 29,999m².

Given the published guidance has been in existence for some considerable time it is reasonable to assume that building population densities were either 1 person to 12m² or 14m² (1:12 or 1:14) at the time of writing.

Based on a density of 1:14 this would give the following range of population:

Minimum 10000 x 0.8 (utilisation) = 8000m²

8000/14 = 571 people

Maximum 29999 x 0.8 = 24,000

24000/14 = 1417

Range 571 – 1417 people; a spread of 846 people.

If we were to take the same criteria but at a population of 1:8 we have the following:

Minimum 10000 x 0.8 = 8000m²

8000/8 = 1000 people

Maximum 29999 x 0.8 = 24,000

24000/8 = 3000

Range 1000 – 3000 people; a spread of 2000 people.

Both the minimum and maximum points increase:

Minimum: 1000/571 x 100 = 175%

Maximum: 3000/1417 x 100 = 211%

Both show significant differences based purely on using the floor areas and relating it to population. At the extremes the population can vary from 571 to 3000 people, served by a single goods lift.

Using the waste criteria detailed in BS5906 [8] these figures translate into the following volumes:

Per week:

571 x 50 = 28,550 litres/week

3000 x 50 = 150,000 litres/week.

A spread of 121,450 litres a week, a difference of some 425%

Taking a more realistic approach, for example a 46,500m² building (circa 500,000² ft) at a density of 1:8 @ 80% utilisation we have:

46,500 x 0.8 = 37,200

37,200/8 = 4650 people.

Based on BS5906 [8] criteria this would generate a waste volume of 232,500 litres per week or 46,500 litres per day over 5 days.

The use of Eurobins, which come in various sizes measured in litres, is a major means of transporting waste. This can be seen for both domestic and commercial waste where collection vehicles are designed to accommodate various bin sizes as part of an automated process.

If the waste is disposed of in 1100ltr Eurobins this equals 43 bins per day that need to be transported to and from the loading bay. If separation into waste streams is also considered it is quite possible the number of bins could double, albeit they may well be of a smaller capacity.

Waste bin movements monitored each evening in a 1sq ft building [2] with a population density of approximately 1:10 (7435 people assuming full attendance) shows the following:

	Out	Returned	Bin Capacity
Assorted waste	50	50	1100ltr
Residual waste	50	50	1100ltr
Food waste	18	18	240ltr
Bin cleaning	6	6	Various
Totals	124	124	**248** bin movements per night

Bearing in mind that this only considers waste removal then the number of journeys required to cycle the bins is considerable.

While it is necessary to consider the goods in, waste out, approach there are other calls on the services of goods lifts. Interfloor traffic where there is a consolidated tenancy, or one tenant occupies several floors within a multi let building, the use of the lifts by back of house staff, the distribution of post and courier deliveries together with tenant fitout works requiring the movement of both materials and personnel all needs to be accommodated.

13 CONCLUSION

The key conclusion reached to date is that goods lifts should not be viewed in isolation but form part of an integrated approach to the management of building logistics. This approach encompasses a much wider range of considerations than the lifts as standalone entities within the building design.

The size and capacity of the goods lifts can be determined in the first instance by establishing:

- The use of the lifts for plant or glass replacement. The sizes and volumes of items to be moved.
- The sizes and weights of building materials that will be used as part of the building construction and fit out works. Floor to floor heights could be a key factor in determining the lengths of materials to be carried. It should be remembered that packaging and means of moving the items are also a consideration.
- The means of moving the materials; on pallets, in wheeled caged trollies, Eurobins or stillages. Establishing the likely sizes of each and the means of moving goods should inform the car configuration in terms of accommodating the maximum number of pallets, trollies and bins within the car.

The volume of goods, materials and waste to be carried leads to the conclusion that the capacity of the lifts is determined by what needs to be accommodated, both during construction and the operation of the occupied building.

From the above there are multiple factors to be considered when trying to establish the number of lifts required. The current CIBSE guidance [6], based on a calculation of usable floor area covers a wide range of both population levels and waste generation. Other factors such as loading bay capacities and management, delivery patterns, the means of moving goods and the wider understanding of building logistics are all things that need consideration and will form the basis of further research by the author.

From the authors works to date it appears there are two potential methods of establishing the number of goods lifts required:

1. To undertake a complete assessment of the variable factors discussed above and seek to model lift usage using simulation. Establishing round trip times, interfloor traffic demand, delivery patterns etc, is complex given these will vary greatly depending on a number of variables, however, it does merit serious consideration when looking at the wider part goods lift play in managing building logistics. This approach is worthy of further research given the final conclusions may well provide a means of using a simulation programme to establish the number of goods lift required in a meaningful way.
2. To utilise the existing CIBSE Guide D [6] method of equating usable floor space, and resultant population, to the number of lifts required, albeit taking consideration of guidance such as BS5906 [7] and the increased levels of office densities, together with changing delivery and operational patterns of modern office.

The provision of public assessible spaces needs special consideration. A roof top restaurant will certainly require dedicated goods lift provision. Any attempt to make the building goods lift serve the restaurant will have a severely detrimental effect on the operation of the goods service to the remainder of the building if not calculated in from the concept design stage.

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BIOGRAPHICAL DETAILS

Len Halsey spent a major part of his career with Otis before joining Canary Wharf Contractors in 1998. He is the Project Executive for Vertical Transportation Systems and is responsible for directing Architects, Consultants and Engineers on VT related design matters to meet Canary Wharf and client’s standards. He is a member of CIBSE and is the current chair of the CIBSE Lifts Group.

Appendix A

Typical means of moving goods within buildings.

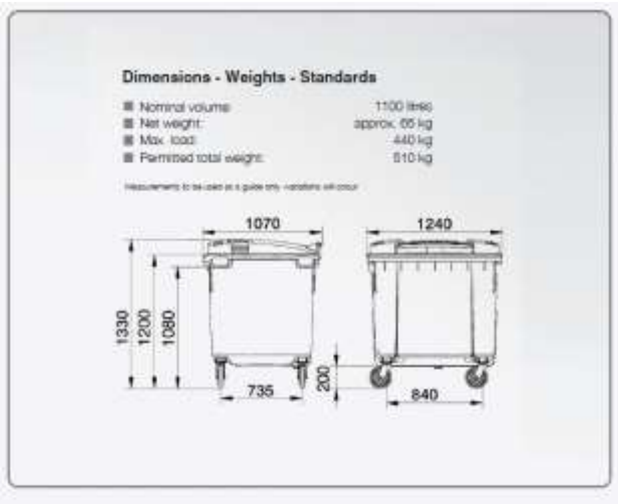
Pallets

The most common size for pallets is 1200mm x 1000mm. Typical loading capacity is 1000kg to 1250kg, but they can be capable of carrying 2500kg. Transported by using hand pulled or electrically operated truck or fork lift. The lift door opening needs to be wide enough to accommodate the full width of the pallet (1200mm) with space to spare to allow for 'operator error' in aligning the pallet with the doors.

Eurobins

These are used extensively in the removal of waste both during construction and the ongoing life of the building. The largest and perhaps most widely used on construction sites and in waste management is the 1100 litre capacity bin

1240mm wide x 1070mm deep and 1330mm high they have a load capacity of up to 440kg.



Caged trollies

Caged trollies are also used extensively in deliveries and distribution of goods. The trollies come in a variety of sizes but can have high capacities of up to 600kg. With 4 wheels and swivel steering they offer a flexible means of managing and manoeuvring goods from the point of delivery to their destination.

Overall dimensions: 735D x 850W x 1690Hmm

How Many Breakdowns Are Acceptable?

David A. Cooper

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Keywords: breakdowns, callouts, obsolescence, appropriate equipment, vandalism, training, skills, MTTF, MTBF

Abstract. The number of acceptable breakdowns that a lift may experience is an emotive subject. There appears to be only one published record that says that four breakdowns per annum are acceptable before an interest should be taken into the reasons why [1]. The owner of the lift may also have a different view of the acceptable number of breakdowns compared to the contractor. There are also a number of variables that have an input into the number of breakdowns that actually occur – age of equipment, external influences (power cuts etc.), type of equipment compared to environment, type of occupant, skills level of maintenance operative, type of maintenance contract, whether maintenance is even being undertaken, and also the number of landing doors being a few. The question is…. can an acceptable number of breakdowns be agreed upon subject to the equipment being the right type for the right environment?

1 INITIAL VIEW

When people are asked how many breakdowns per annum are acceptable on a lift the response will be a wide range of opinion.

Some lift owners will say that no breakdowns are acceptable with some maintenance contracts applying penalties for downtime.

At the other end of the scale a lift maintenance contractor on a basic oil and grease contract will rub their hands in financial delight at the thought of a breakdown as they can charge for attendance!

An employee in a building might not care how long it takes them to get to their workplace so if the lifts are regularly out of service they might be ambivalent to it whereas their employer might have a different view.

2 CASE HISTORY

In a recent civil dispute which went legal but settled prior to trial a tenant claimed against the landlord for enduring years of poor lift service in a building which they occupied several floors. Table 1 below shows the difference between the claimants' position and that of the defending landlord.

The claim was that there had been hundreds of lift breakdowns in the period and that the landlord, and its servants (the facilities management company and the lift maintenance contractor) had failed to manage the building in a professional manner.

Long and detailed analysis of hundreds of documents revealed that apart from over occupying the building the list of breakdowns included items such as light bulbs failing in a lift car, fire alarm activations and subsequent lift groundings, power cuts, lifts being left on car preference and so on.

The final analysis was that, whilst the number of breakdowns was high, it wasn't anywhere near as high as the claimant suggested despite the millions of pounds involved in the claim.

Year	Claimant		Defendant	
	Total	Per lift	Total	Per lift
2008	96	13.7	63	9
2009	129	18.4	101	14.4
2010	102	14.6	86	12.3
2011	199	28.4	151	21.6
2012	206	29.4	132	18.9
2013	94	13.4	69	9.9
2014	81	11.6	67	9.6
2015	34	4.85	18	2.6

Table 1 Comparison of total breakdowns claimant versus defendant

Further analysis was undertaken as to the causation of the various breakdowns by tabulating breakdowns where:

- Components were required
- Minor maintenance was required
- Misuse
- No fault found/working on arrival
- Fault not detailed

Type of Call/ Incident	2002	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Breakdown call requiring parts/ repair	0	0	0	0	42	43	20	50	19	19	4	0	**197**
Minor maintenance	0	0	0	0	3	29	43	76	59	33	35	0	**278**
Misuse	0	0	0	0	2	1	1	1	1	0	2	2	**10**
No fault found/ running on arrival	0	0	0	0	1	13	10	6	9	2	2	0	**43**
Fault not detailed	5	3	1	3	15	15	12	18	44	15	24	16	**171**
Total	**5**	**3**	**1**	**3**	**63**	**101**	**86**	**151**	**132**	**69**	**67**	**18**	**699**

Minor maintenance includes resets after power failures

Table 2 Analysis of breakdown causation

Table 2 reveals that whilst the majority of breakdowns were as a result of minor maintenance being required (more often than not doors going out of adjustment) there were also issues with component replacement being required on a regular basis. In truth the lifts had been neglected and poorly maintained.

The above table also reveals that reporting by the maintenance contractor in 171 cases was such that no proper analysis could be undertaken of those breakdowns.

Further analysis as shown below in figure 1 below revealed that the number of passenger entrapments were found to be high and it was in fact this situation that alerted the tenant to the problems as staff were claiming to be scared to use the lifts.

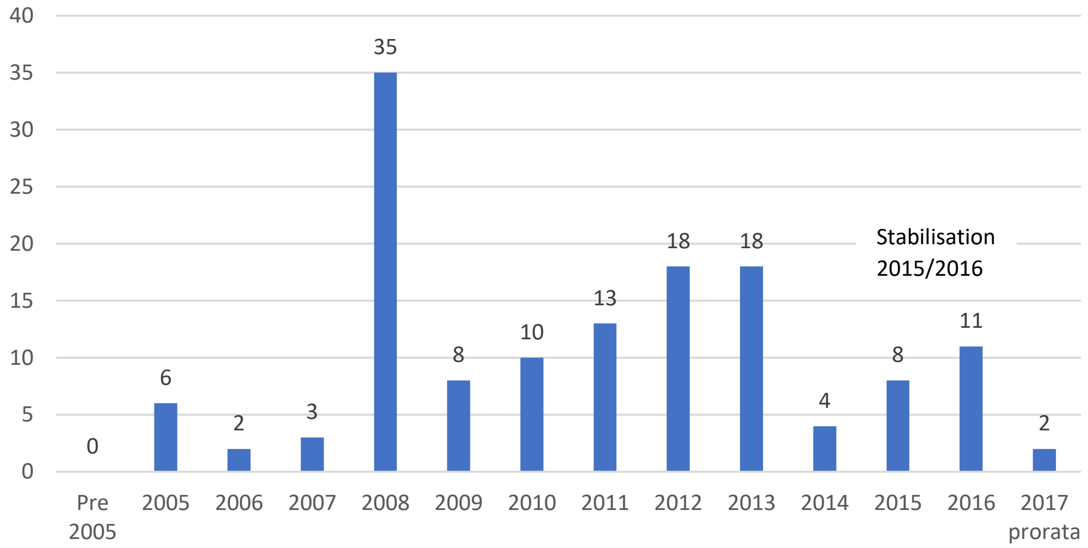

Figure 1 Number of passenger entrapments by year

3 WHAT IS A BREAKDOWN?

In order to agree on a relevant number of breakdowns it is required that a definition of a breakdown be agreed.

There are a number of definitions of what a breakdown is and these can be broken down into two types, namely:

- Total Breakdown
- Depleted Service

For instance, a door lock fault that is on permanently and renders the lift out of service can be described as a total breakdown whereas a stuck push button may place the lift into a depleted service where the lift will only stop at that floor occasionally rather than being stuck there permanently as was the case before stuck button recognition.

For the purposes of this paper the definition used for a breakdown is one which leaves the lift out of service and unable to respond to any calls.

For the purposes of clarity issues such as a defective indicator, defective safety edge where nudging is fitted where the contractor has been called to affect a repair is not considered a breakdown.

4 SUB LEVEL OF BREAKDOWNS

There is a sub level of breakdowns which need to be removed from the total breakdown count and these include:

- Vandalism where appropriate equipment has been installed.
- Power cuts

- Card reader (security system) failure
- Grounding as a result of fire alarm inputs
- Lift left on car preference control
- Obstruction in door track

In simple terms a breakdown where the causation of the breakdown is as a result of an external influence and not as a result of a component failure or poor maintenance.

In addition, callouts labelled as working on arrival should be removed from the equation as these cannot provide substantive evidence as to the cause of failure however it is recommended that where these are excessive they should be considered as a separate data set.

5 ACCEPTABLE NUMBER OF BREAKDOWNS

Only one published reference to an acceptable number of breakdowns has been found in which it says that four breakdowns per annum can be considered acceptable[1].

This reference is not specific as to the environment in which the lift in installed.

This raises the question whether the acceptable number of breakdowns should vary for different environments?

Maybe one would have an opinion that a hospital environment should have less than a social housing environment and so on.

This may well promote social debate especially as there is currently a situation where social housing residents are critical of local authorities for value engineering construction projects. There has been nothing more evident than the Grenfell Tower fire for this discussion.

The lift industry finds it acceptable to apply a different average interval and handling capacity to private residential dwellings than it does to social housing which begs the question as to whether the approach is correct or not. Table 3 below sets out the published difference in CIBSE Guide D [2].

Table 3.13 Design criteria: residential buildings (5-minute, two-way)

Type	Luxury	Normal	Low income
Interval (s)	45–50	50–60	50–70
Two-way handling capacity (%)	8	6–8	5–7

Table 3 Different approach to residential dwellings with respect to traffic design

The question of where the lift(s) are in their lifecycle should also be considered. Figure 2 below sets out a graphical representation of equipment life as published in the claimant's experts report[3] (source not known). If they are in phase 1 of their life and appropriate equipment has been installed it would not be appropriate to consider modernisation or replacement.

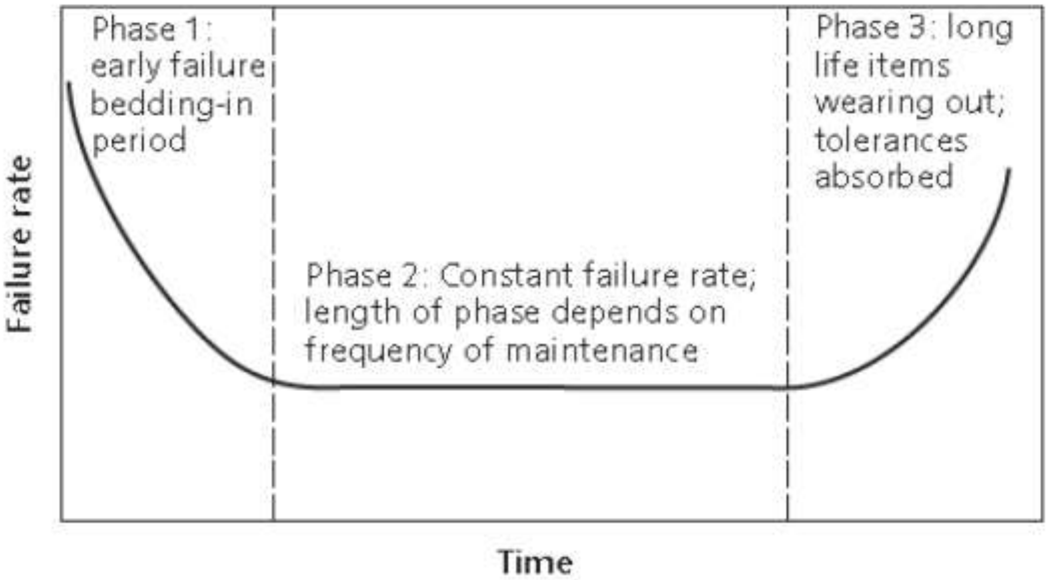

Figure 2 Phases of equipment life

In addition, consideration needs to be given to advice from control panel component manufacturers with respect to Mean Time to Failure (MTTF)

In a real case of a brake failure on a lift as a result of the lift driving through the brake, the contactor manufacturer had established a MTTF or number of operations the contactor could be expected to last as being 1 million operations.

The MTTF is established by testing a number of similar components until they fail and averaging the number of operations.

The location of the lift was a high-rise residential tower block of around 20 levels. With two lifts in the block and 6 dwellings on each landing mostly containing two persons it is not unreasonable to estimate that the lifts would have made 960 starts per day (6 x 2 x 4 x 20) or 480 starts each. This is based on a simple rule of thumb that every occupant did a return journey in the lift twice in a day but doesn't allow for the postman, milkman etc who may use the lift to stop at every floor.

On that basis of this rule of thumb the contactor could be expected to last 2,083 days or 5.7 years. In this case the control panel was around 20 years old and the contactor was thought to be the original but it does demonstrate that scheduled component replacement should be considered especially as control panels are expected to last between 10 and 15 years on average. Journey counters would be useful on all control panels to assist with a MTTF component replacement strategy.

6 REPEAT CALLOUTS

Repeat callouts can occur for many reasons including an intermittent fault that only raises its head every now and again either because of the nature of the defect or as a result of circumstances coming together to make the fault appear (a perfect storm).

To those affected by such a situation the fact that the fault is intermittent is annoying but also very real and as far as they are concerned they will see them as separate breakdowns because to them they are whereas to an industry operative they might see it as one breakdown that took X number of visits to solve.

In one case the safety gear on a lift operated over 30 times in a year as a result of incorrect installation as the governor rope was run through rough cut holes cut in the guide brackets yet nobody from the contractor diagnosed the cause.

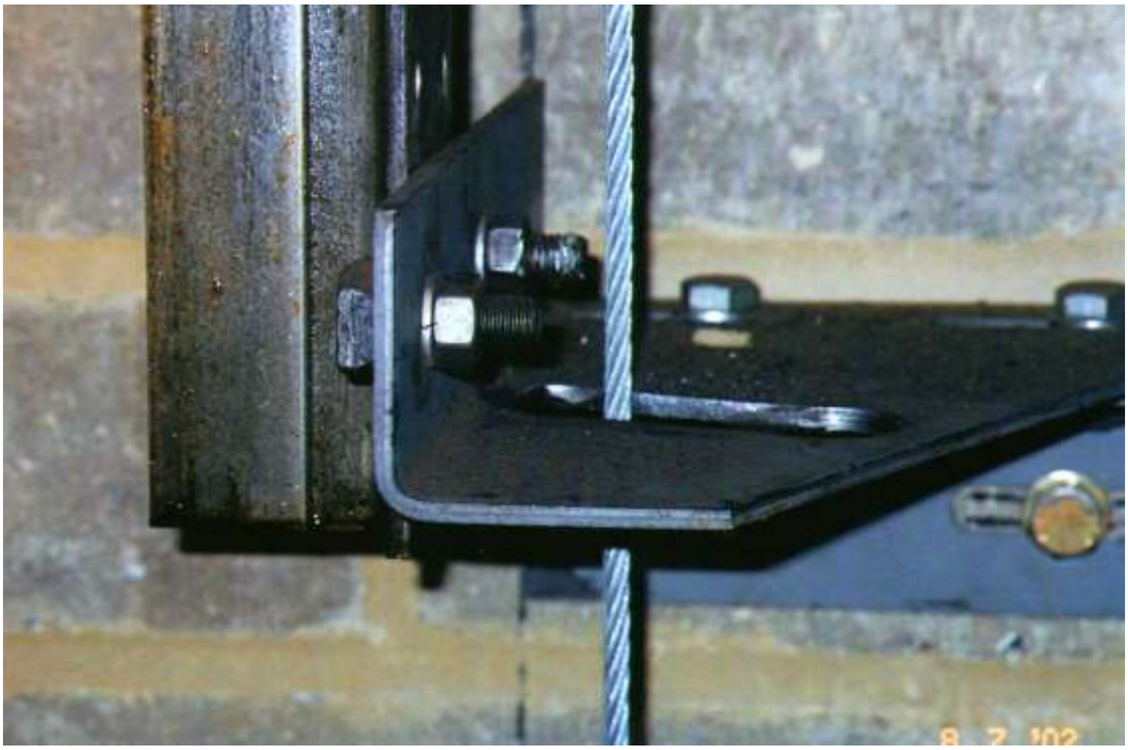

Figure 3 Incorrectly installed governor rope

7 WHAT IS A CALLOUT AND HOW SHOULD THEY BE CLASSIFIED?

Examples of different callouts (note callouts not breakdowns albeit some of the callouts can be deemed breakdowns) to lifts are tabulated below and the difference in claimed outcome can be seen.

Table 4 below is purely hypothetical and is intended to provoke debate.

Callout reason	Number of callouts	Possible claimants view on number of callouts	Possible defendants view on number of callouts
The lift was found to be on car preference and re-entered service immediately after this was removed.	5	5	0
The lift was found not to have been "working" because it has shut down in energy saving mode as it was deemed by the control system that the other lifts provided sufficient service	3	3	0
The lift had clipped a lock at the 3rd floor three days in succession but then restarted but the contractor had not been called.	3	3	1
The lift had clipped a lock at the 3rd floor three days in succession and the contractor had not been called on each occasion.	3	3	3
There had been a total power cut in the building	4	4	0
The safety edge had been vandalised	2	2	0
The lift had crash stopped in travel over a period of a month. It was found that there was a break in a trailing flex that intermittently dropped the safety circuit. On most occasions the lift restarted as the break remade and the fault wasn't diagnosed until the break became permanent.	5	5	1
A lamp in the lift car failed	3	3	0
Total		28	5

Table 4 Hypothetical Callout Table with possible different stances

The customer experience isn't good but it is far from being the fault of the lift itself.

8 ACTIONS WHEN BREAKDOWNS APPEAR EXCESSIVE

Even if it was agreed that four breakdowns a year were acceptable that shouldn't automatically initiate a programme of modernisation or replacement.

The maintenance contractor should review the contract and ask the following questions:

- Is the equipment installed appropriate for the location?
- What is the age of the equipment installed?

- Is the equipment installed obsolete?
- Are the breakdowns being caused by a single or multiple cause?
- Does the location suffer from misuse?
- Is the number of breakdowns high due to a single issue that hasn't been properly diagnosed or rectified?
- Is the maintenance operative suitably skilled for the task/equipment?
- Is technician support provided in an appropriate and timely manner?

Once an analysis has been undertaken the owner/operator should seek independent advice from a suitably qualified consultant to avoid a possible commercial bias from the contractor.

Following this the owner should ask the following questions:

- Is the maintenance contractor appropriate for the equipment installed?
- Is the maintenance operative suitably trained?
- Are breakdowns escalated to a more appropriate technician when required?
- Is the type of maintenance contract suitable for the location?
- Has an agreed causation of breakdown analysis been undertaken?
- Does the location suffer from misuse?
- How can the analysis and information be taken forward?

9 CONCLUSIONS

A standard X number of breakdowns per annum is not an appropriate way of measuring the need for modernisation or replacement.

It may however alert an owner and/or maintenance contractor to the fact that problems exist.

Over and above this:

- It might also be more appropriate to say "the acceptable number of breakdowns is X on the basis that appropriate equipment is installed"
- Discussion is required as to an appropriate level of breakdowns based on the locus.
- Reliability is just as important as a design based on traffic analysis
- Detailed reporting of breakdowns by the maintenance contractor is a must to allow adequate analysis to be undertaken.
- Tenants are seeing the opportunity to claim against contractors and/or building owners for poor lift performance.

It is the authors' opinion that only once a true picture of breakdowns versus callouts has been established that a discussion can be had as to whether modernisation or replacement are appropriate.

It is however important that an appropriate maintenance regime considering MTTF and undertaken by properly trained staff needs to be in place and be monitored. This should include staff being trained in how to complete log cards and maintenance records.

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BIOGRAPHY

EurIng David Cooper

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

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

Investigations on Safety Measures for Lifts and Escalators; Outcomes from the Researches Funded by the Building Standard Development Promotion Program, Japanese Ministry of Land, Infrastructure and Transport (MLIT)

(Loading Tests for Full-scale Model to Confirm the Critical Strength of Existing Escalator Truss During Severe Earthquakes)

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Keywords: escalator, truss structure, seismic motion, full scale loading tests, elasto-plastic deformation, analytical model

Abstract. For the existing escalators, the fall-off phenomenon on the side where the support interval widens during earthquake can be dealt with by lengthening the supporting margins. However, because the problem on the compression side is difficult to deal with, experimental and analytical studies were carried out to clarify the elasto-plastic restoring force characteristics of the escalator-truss structures and to refine and improve the seismic design guidelines and the Japanese building standard law, and its enforcement order. Series of experimental tests were carried out by using actuator/jack-testing apparatus of Tokyo Denki University. This project was supported by the building standard development promotion program conducted by the Japanese ministry of land, infrastructure and transport (MLIT) in order to improve and maintain the Japanese building standard law, and its enforcement order by applying non-government organizations such as research institutes, private enterprises and universities.

1 INTRODUCTION

The devastating earthquake of Mw9.0 hit the Tohoku district, northeast part of Japan on March 11, 2011. About 16,000 people died and 3,000 people were missing due to the strong motion and the tsunami. The economic damage was estimated about 16.9 trillion yen (115 billion British Pounds) excluding the influence by the nuclear accident of Fukushima Daiichi Nuclear Power Plant. In addition to the main shock, many strong aftershocks occurred in the long term until June in 2011. The industrial facilities, power plants, or research facilities were damaged in these earthquakes, and various kinds of mechanical equipment set in these facilities were damaged.

During this earthquake, four fall-off accidents of the escalators, utilized in three steel framed shopping mall buildings, occurred. One of the main causes of the fall of escalators is due to the lack of sliding margin of the non-fixed joints between the escalator-truss and the supporting beam mounted on the building horizontal frame due to the unexpected excessive story-deflexion of the building structures caused by the earthquake. The other causes are considered that the escalator-truss structures collide with the supporting beam, as described above, in the non-fixed end and the compression force induced during collision might give elasto-plastic deformation and residual displacement to the escalator as a result. In this case, the escalator might not only lose the vertical load supporting ability but also the shortening of the length of the truss might reduce the sliding margin.

For the existing escalators, the fall-off phenomenon on the side where the support interval widens during earthquake can be dealt with by lengthening the supporting margins. However, because the problem on the compression side is difficult to deal with, experimental and analytical studies were carried out to clarify the elasto-plastic restoring force characteristics of the escalator-truss structures and to refine and improve the seismic design guidelines and the Japanese building standard law, and its enforcement order. Series of experimental tests were carried out by using actuator/jack-testing apparatus of Tokyo Denki University. And this project was supported by the building standard development promotion program conducted by the Japanese ministry of land, infrastructure and transport (MLIT) in order to improve and maintain the Japanese building standard law, and its enforcement order by applying non-government organizations such as research institutes, private enterprises and universities.

1.1 The building standard development promotion program conducted by the Japanese ministry of land, infrastructure and transport (MLIT)

The Ministry of Land, Infrastructure, Transport and Tourism announced a survey project with the issue of "Study on securing safety of existing escalators against earthquakes" in order to prevent future escalator fall-off in coming severe earthquakes such as earthquakes directly under the capital city, Nankai Trough Earthquake and so on. Regarding this subject, Fujita Laboratory and Tachibana Laboratory of Tokyo Denki University, and Japan Elevator Association planned and considered the following contents for this issue.

1) In order to verify the case where the main structure of the existing escalator (truss structure and beam structure, hereinafter referred to as "truss etc.") was compressed by the seismic load induced in the building beam during severe earthquakes, the experimental tests were conducted. And, simulation analysis was followed for newly utilized and existed escalator trusses to clarify the buckling behaviors of trusses under various conditions in which the joining conditions of members.

2) The compression experimental tests of a full-size truss etc. were carried out to demonstrate the validity of the simulation analysis from the comparison of the simulation analysis results with the experimental results.

3) From these results, even in the case of receiving compressive force from building beams induced by the excessive story drift due to severe seismic inputs, it is to demonstrate that the truss etc. of the existing escalator is safe against fall-off and to clarify the conditions that need to be confirmed in the design stage. In addition, we propose a draft standard that confirmation by actual size experiment can be omitted.

The Building Standards Development Promotion Program will publicly invite business operators such as university corporations to gather technical knowledge etc. for the improvement of technical standards pertaining to the Japanese Building Standard Law, etc. by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The results of the survey are compiled according to the survey items and recommendations are proposed for the building standard laws concerning structural design methods and so on.

1.2 Escalator fall-off damage occurred in the 2011 off the Pacific coast of Tohoku Earthquake of March 11, 2011

The 2011 off the Pacific coast of Tohoku Earthquake (hereinafter referred to as " Great East Japan Earthquake") that occurred at 14:46 JST (05:46 UTC) on Friday 11 March 2011, with the epicenter approximately 70 kilometres east of the Oshika Peninsula of Tōhoku and the hypocenter at an underwater depth of approximately 29 km is a huge earthquake that recorded the seismic intensity 7 (moment magnitude Mw=9.0), and the large scale tsunami spread to the Pacific coastal area immediately after the earthquake. After that, aftershocks continued to occur for a long period of time until July, and both the main shock and aftershocks caused damages to the lifts and escalators, which are building facilities, along with the buildings in a wide area from the eastern Japan area to the Kanto, Hokuriku and Chubu areas.

Due to the main shock, four escalators that were installed in three shopping malls dropped from the upper floor to the escalator on the lower floor. Figure 1a, 1b and 1c respectively show examples of fall-off accidents of escalators [1]. Because, in conventional seismic design for shopping centre design as described in 1.3, value of story drift is becoming extremely large especially against the severe earthquake such as Great East Japan Earthquake, the criteria of the overlap allowance between escalator truss and the lateral beam of the building where the escalator is placed on must be reviewed.

Figure 1a Shopping centre in Saiwai-cho, Sendai City

Figure 1b Shopping centre in Izumi-Osawa, Sendai City

Figure 1c Shopping centre in Koriyama City, Fukushima Pref.

1.3 Conventional seismic design of building

Table 1 shows the calculation method of building story drift angle against marginal earthquake ground motion for the seismic design of building structures by the Japanese building law. In seismic design of shopping centre buildings, Type (D) design method is usually used. If the story height of the building is 4,000 mm for example, the story drift deformation is obtained as follows.

$$4{,}000 \times \frac{1}{24} = 166.7\ mm$$

Although this value itself is very large, it is confirmed that the story deformation angle in these types of building exceeds 1/30 even in a real scale large building earthquake resistance experiment using a large shake table. Therefore, it was confirmed that this value must be considered when the escalator is installed.

Table 1 Calculation method of building story drift angle for marginal earthquake ground motion

Type of design		Story drift angle must be considered
(A) 5 times the story drift angle (within 1/200 in principle) of the building calculated by usual calculation (Japanese Building Standard Law Enforcement Ordinance Article 82-2)	➡	**1/40 in principle**
(B) Steel structure with small amount of deformation, reinforced concrete structure that can be calculated using allowable stress degree calculation (Route 1)	➡	**1/100 or more**
(C) Large scale buildings etc. which obtained the story drift deformation angle by special investigation and research (time history response analysis and limit strength calculation)	➡	**If the calculated value is less than 1/100, it is 1/100 or more**
(D) When not obtained by structural calculation	➡	**1/24 or more**

2 CRITERIA OF LAWS AND ORDINANCES AT THE TIME OF THE TOHOKU GREAT EARTHQUAKE

When expressing the magnitude of the shaking of the building during an earthquake, not only do you express the response acceleration, but also the amount of story deformation or the story drift angle.

Recently, after these fall-off accidents, in the design stage for installing escalators in buildings to be newly built, the designer of the building considers and presents the value of the story drift deformation or the story drift deformation angle of the building calculated from the response analysis against the design earthquake inputs to the designer of the escalator, then the designer of the escalator considers fall prevention countermeasures etc.

On the other hand, in the case of existing escalators, they are designed according to laws and regulations prior to the current law, elevator seismic design and construction guidelines, etc. For this reason, the "clearance" between the building and the escalator or the overlap allowance sometimes does not satisfy current laws and regulations. Figure 2 shows the clearance between the escalator truss and the building beam and the overlap allowance.

In the case of an existing escalator installed with less "clearance", when the building shakes greatly due to the severe earthquake inputs, the "gap" decreases and when the building further shakes, the building beams may hit and collide with the escalator truss structure. When the escalator is compressed from the building, the escalator truss, which is a strength member, receives the most of its forces and deforms by the compressive force. In addition, when the overlap allowance is not sufficient to the displacements, it can be assumed that the supporting angle of the escalator will come off the beam of the building due to the large sway of the building.

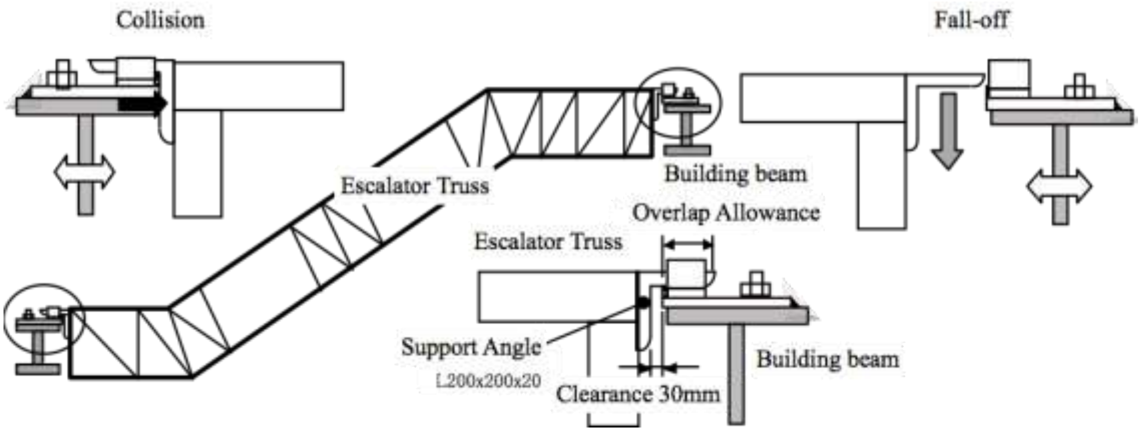


Figure 2 Clearance between the truss and the building beam and overlap allowance

3 EXPERIMENTAL TEST FOR CONSIDERATION OF DEFORMATION OF ESCALATOR TRUSS DURING SEVERE EARTHQUAKE

3.1 Consideration of deformation of escalator truss during severe earthquake

In the escalator truss, in general, members such as upper chord members are arranged in the same direction as the horizontal axis direction. For this reason, when a building causes large story deformation in the same direction of the horizontal axis direction of the escalator due to seismic inputs and the escalator truss is compressed and deformed in the same direction, the truss members are deformed and might cause buckling deformation, and then strength of members will be greatly reduced.

On the other hand, when the story drift displacement in the orthogonal direction occurs, the escalator truss shows rotational displacement in either one of the upper end or the lower end as the rotational centre, so that compared with the case that the escalator truss is forced and deformed in the horizontal axis direction, the deformation of the truss member is considered slight, and the risk of fall-off is considered to be small.

From the above reasons, it was decided to examine whether or not the horizontal axis direction deformation would cause a hazard in safety to the truss member will occur and the strength evaluation method against it.

For that purpose, to acquire knowledge through experiments using real size escalator truss is indispensable. Therefore, an experimental apparatus capable of applying forced displacement in the long side direction to a full-size truss was designed and manufactured, and a full-scale experiment was conducted to confirm the deformation state of the truss. Full-scale experiments to confirm the deformation of escalator trusses were conducted from November 4, 2014 to the end of December, at the Building Technology Research Centre of the Tokyo Denki University Chiba New Town campus.

3.2 Experimental apparatus

The overall view of the experimental apparatus is shown in the installation view of the experimental frame and test specimen (see Figure 3). Experimental situations in which escalator trusses are actually installed are shown in Figure 4 and Figure 5. In designing and manufacturing the experimental apparatus, we considered the following points.

(1) The upper and lower racks and the loading device were designed, manufactured and utilized with the maximum long side direction load of 1,000 kN and the maximum forced displacement amount of 200 mm.

(2) The lower rack on which the support angle of the lower end of an escalator truss is placed is designed to be able to slide in the horizontal axis direction so that the escalator truss can be applied the force for compressing in the horizontal axis direction. This foundation was firmly fixed using a PC steel bar to the reaction force floor of the experiment site.

(3) The lower rack and the hydraulic device giving the force to the truss were connected firmly by rods (PC steel bars). They are provided at two positions on the left and right ends of the truss, and the left and right hydraulic devices are operated synchronously by electric control.

(4) The upper rack, on which the supporting angle of the upper end of a truss is placed, was firmly fixed to the vertically standing reaction wall in the experiment site using a PC steel bar. In addition, in order to prevent the support angle of the upper end from floating up during the experiment, the support angle at the upper end of the escalator and the upper mount were fastened with bolts.

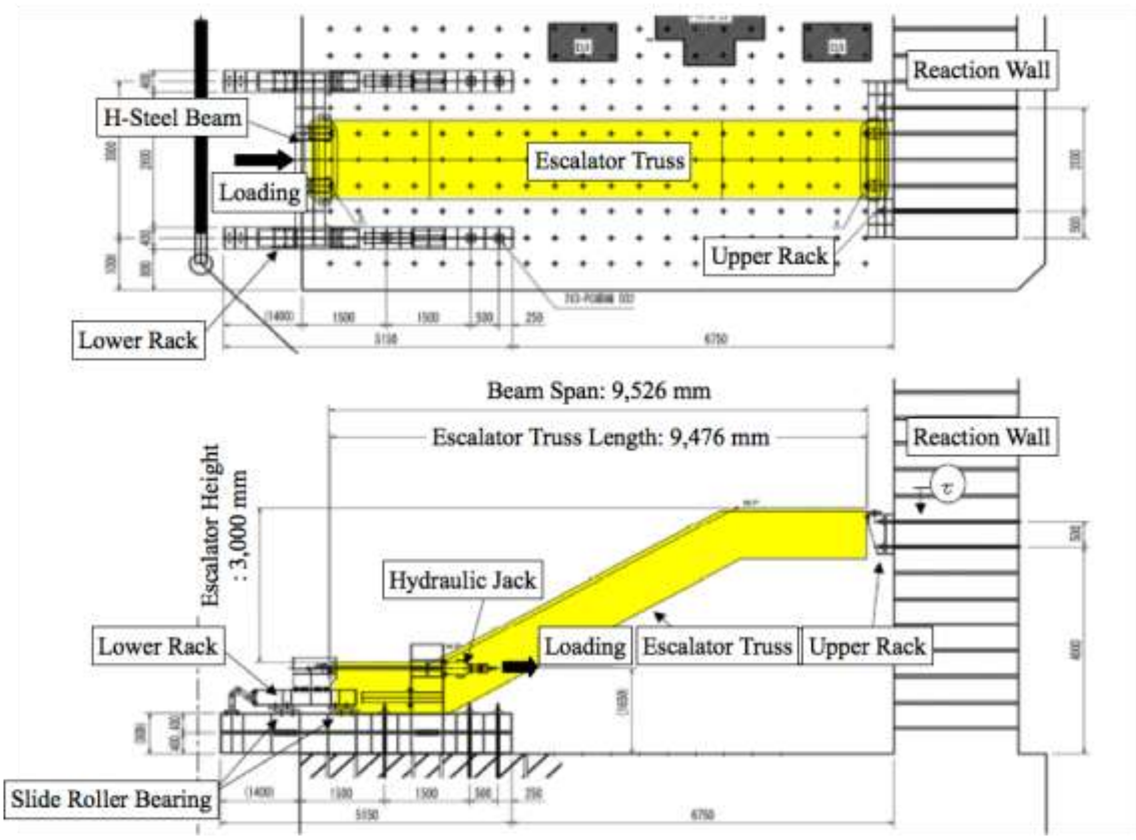
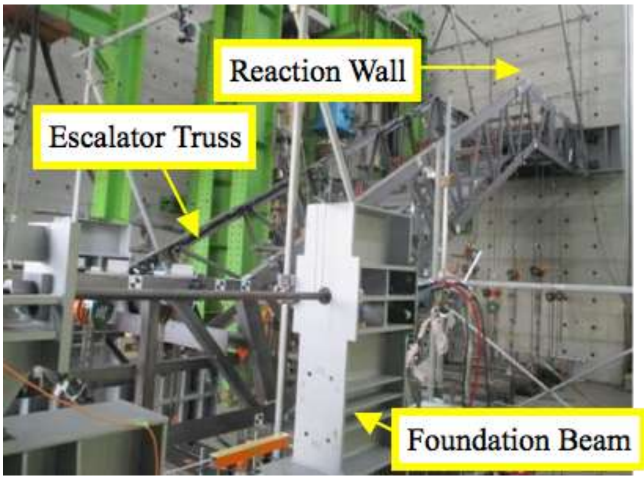


Figure 3 Overall layout of experimental apparatus and test specimen



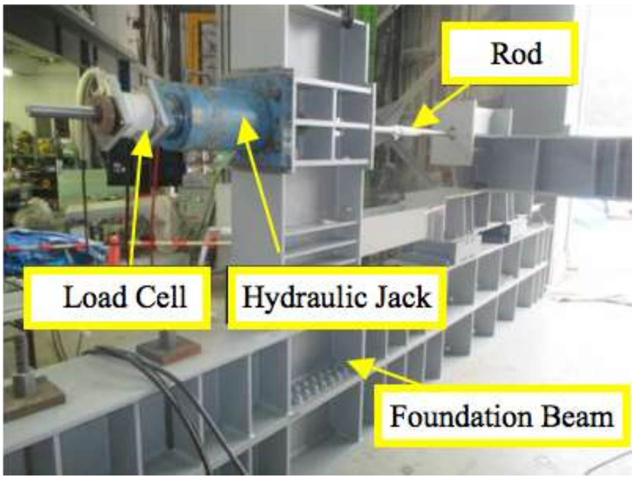
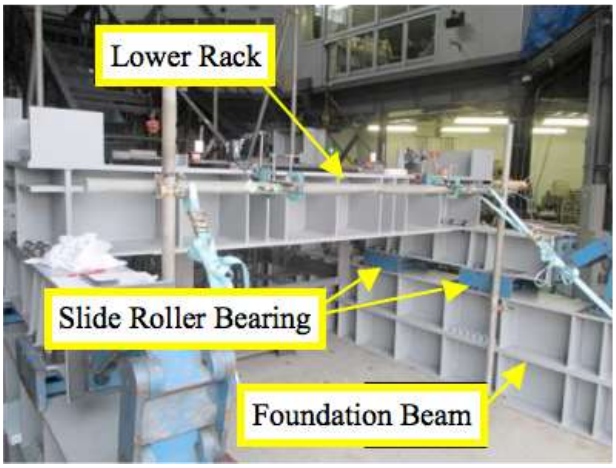


Figure 4 Truss installed to experimental apparatus and test specimen (left) and hydraulic jack for loading (right)



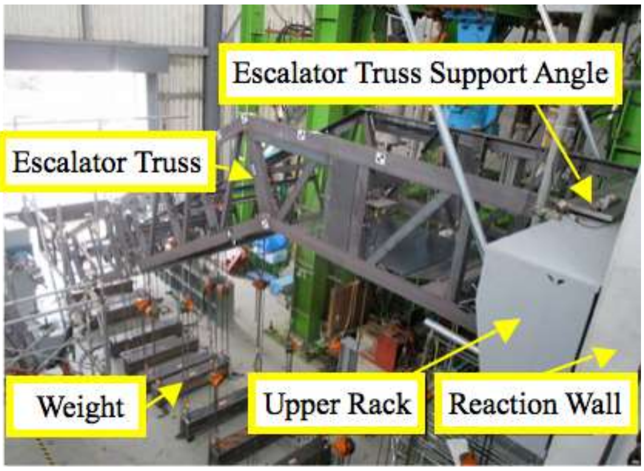


Figure 5 The lower base beam (left), the upper rack and the truss fixed state (right)

3.3 Escalator trusses used for the tests

In a full-scale experiment, tests were conducted using seven truss structures consisting of equilateral angle steels and one with beam structure so that most of the existing escalator truss structures can be covered. The common main specifications of each test specimen are shown in Table 2.

Table 2 Main specifications of the test specimen

Item	Specifications
Floor height	3,000 mm
Step width	Type S1000: 1,330 mm
Slope angle	30 degree
Horizontal step	Standard type
Full length (horizontal projection length)	9,476 mm

Because it is the essential object of this experiment to confirm that the escalator does not cause deformation that would be a hindrance to safety in the case where the escalator underwent forced displacement due to story drift deformation of the building caused by earthquake, only truss structures without any parts such as steps, hand rails and so on were tested instead of using the completed escalator system. In addition, as mentioned above, the escalator internal equipment (Driver Unit, Step, Step Case, Step Rail, Inner Plate, etc.) other than the main body of the truss was not included in the test specimen, and the load of those were loaded by the additional weight and tested. Figure 5 shows test specimen (escalator truss) and installation of additional weight.

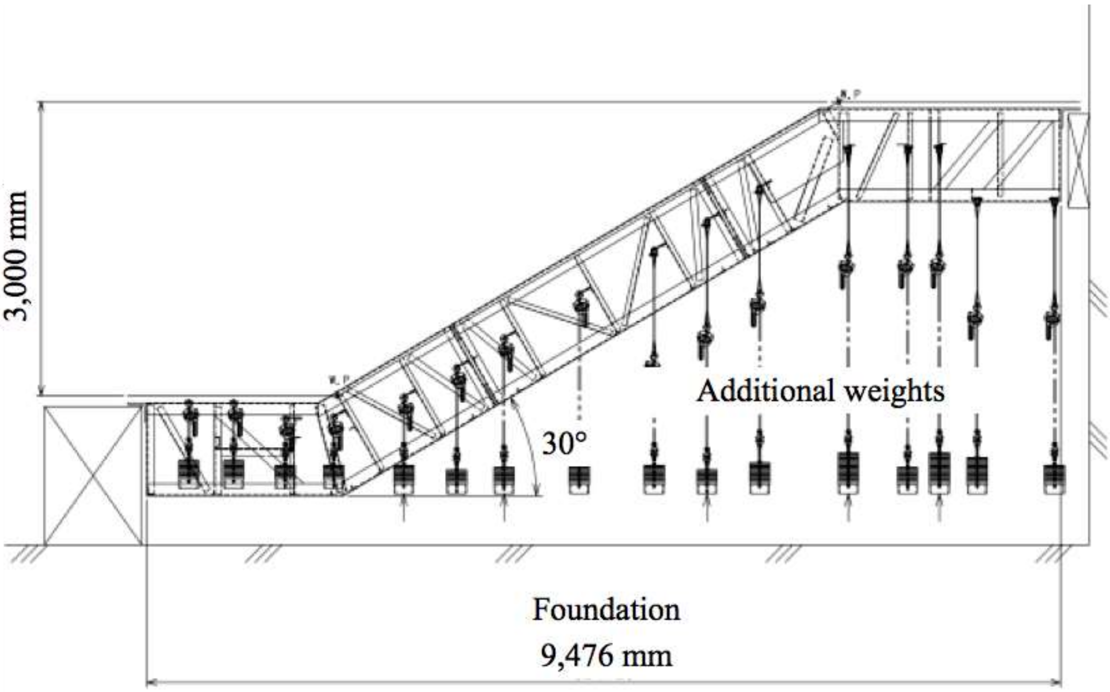


Figure 6 Test specimen and installation of additional weight

3.4 Measurement

Table 3 shows the measurement items and methods in the experimental tests. In addition, in order to observe the behavior of the entire specimen, digital cameras and video cameras were installed and captured.

Table 3 Measurement item list

No.	Item	Measurement method
1	Forced displacement in horizontal axis direction of escalator truss (Compressive deformation)	Forced displacement shall be the value that subtracts the average value of the displacement of the two upper support angles of the specimen from the average value of the displacement of the two support angles at the lower part of the specimen.
2	Horizontal axis direction load	Measure with a load cell attached to each of the right and left hydraulic devices and set it as the total value of the load measured by the left and right load cells.
3	Horizontal displacement	Markers are placed on the part where displacement is measured. Measure the movement of the marker position and determine the displacement by image analysis.
4	Strain induced in the escalator truss	Measure with a strain gauge.

3.5 Loading condition

The vertical load applied to the truss consists of the load of the escalator itself and the internal equipment weight. Since this experiment is carried out only with a truss structure, considering maximum loading load and equipment weight, they are adjusted with additional weight. The loading load was set to 2,600 N/m^2 prescribed in Article 129-12 of the Building Standard Law Enforcement Order and the loading range is assumed to be "step width × total length of the escalator", and the equipment weight was calculated excluding the weight of truss. Additional weights are placed so that the load calculated by these is equivalent to the load distribution of the actual escalator.

3.6 Method of applying force to the specimen

The load applied to the specimen in the horizontal axis direction of escalator truss was not a monotonically increasing load, but the loading and unloading were repeated stepwise several times and compressed until the length in the horizontal axis direction was finally shortened by about 200 mm. This approximately 200 mm corresponds to approximately 1/15 of the story drift deformation angle, which is more severe value than 1/24 of the most severe story drift deformation angle prescribed in Ministry of Land, Infrastructure and Transport Notification No. 1046 as described in Table 1.

The loading plan is as follows and is shown in Figure 7 :

1) After applying a load of 60 kN in the horizontal axis direction, unload it to almost 0 kN.

2) After loading 200kN in the horizontal axis direction, unload it.

3) After forced displacement is applied up to 40 mm, unload it.

4) After 40 mm, forced displacement is applied up to 40 mm to 80 mm, 120 mm, 160 mm in the same way, then unload it.

5) After forced displacement is applied up to the maximum value of 200 mm, then unload it.

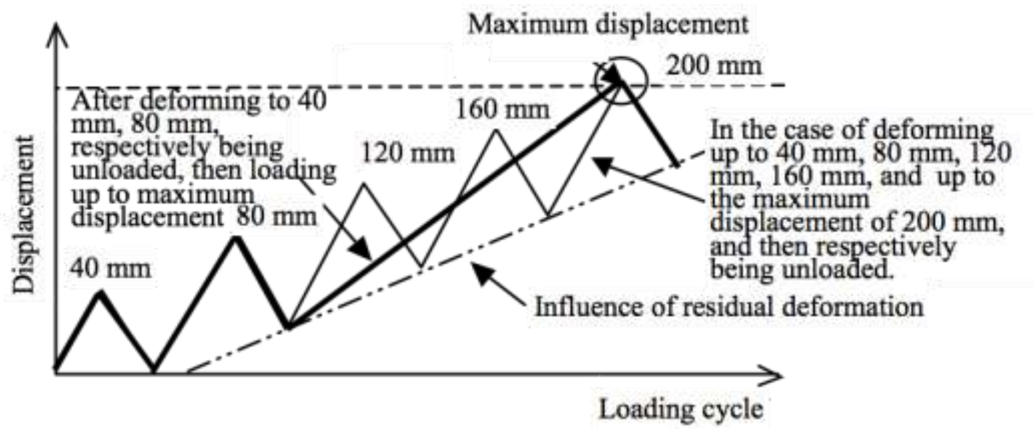


Figure 7 Loading pattern

3.7 Experimental results

In the full-scale experimental tests, a total number of eight truss bodies including a truss structure and a beam structure were carried out. Equipment weight and loading weight other than the weight of the truss structure or beam structure were suspended from the lateral beams of the truss as additional weights with the same weight as each. These additional masses have no effect on suppressing the deformation of the truss structure or the beam structure, so that, in the proof stress assessment after a very large deformation occurred, they do not give the safety side results.

Figure 8 shows restoring force characteristics for all the eight escalator trusses tested. In the beam truss structure, elastic deformation proceeded with increasing forced displacement immediately after the start of applying force and shows the relatively lower stiffness in linear region as compared with the others. When the horizontal axis direction load reached the maximum value, deformation started to occur in the upper chord material of the lower bent portion, and the load in the horizontal axis direction decreased sharply. Because the restoring force characteristics after the stepwise loading started decreasing again on the same hysteretic lines as before unloading, it was confirmed that there was no influence due to repeated loading and unloading.

In the series of experimental tests, the deformation position was the upper chord material located in the lower bent portion or the intermediate part of the diagonal material although the progress of deformation varied depending on each other and on the shape of the section steel used. In addition, in the beam structured escalator truss, deformation occurred at the lower bent portion.

Deformation states of all the types of escalator trusses are respectively shown in Figure 9, 10, 11 and 12.

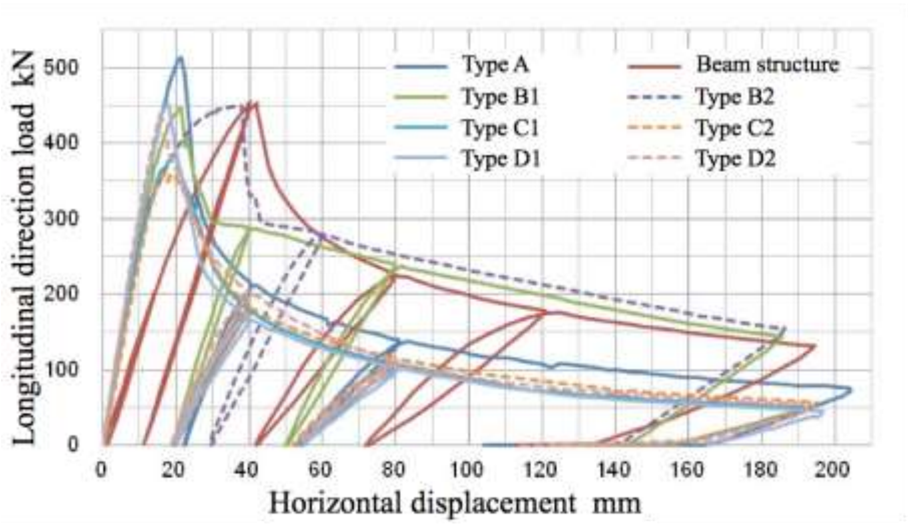


Figure 8 Restoring force characteristics of escalator trusses

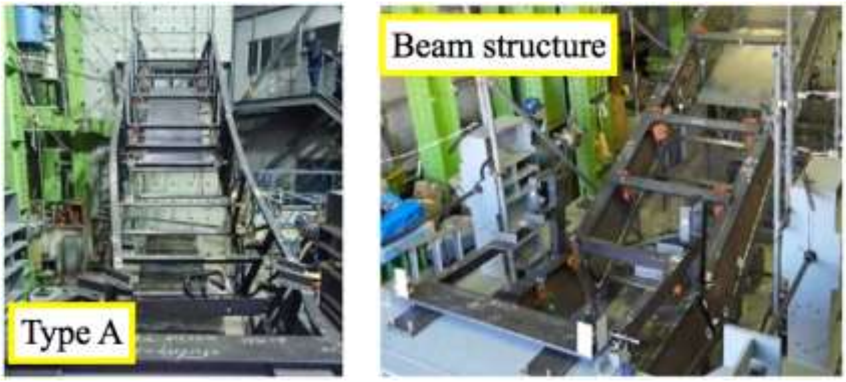


Figure 9 Deformation state of the type A and beam structure escalator truss

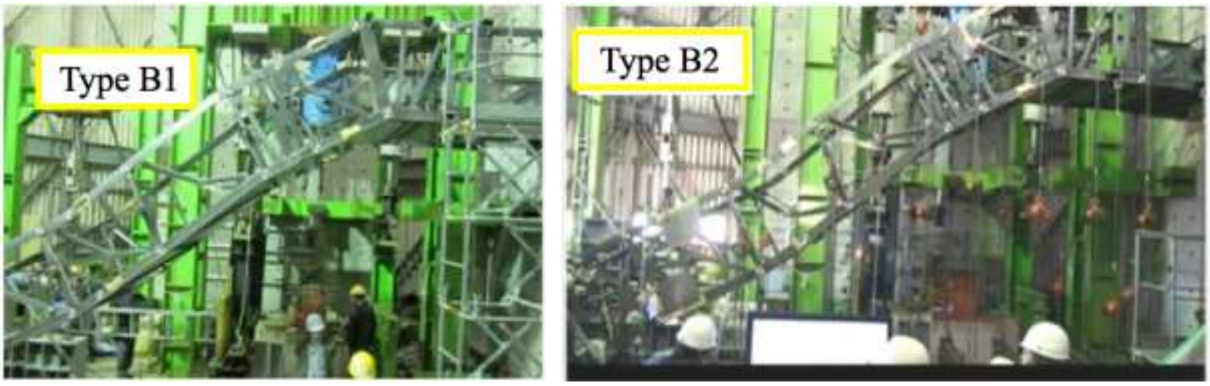


Figure 10 Deformation state of the type B1 and B2 escalator truss

Figure 11 Deformation state of the type C1 and C2 escalator truss

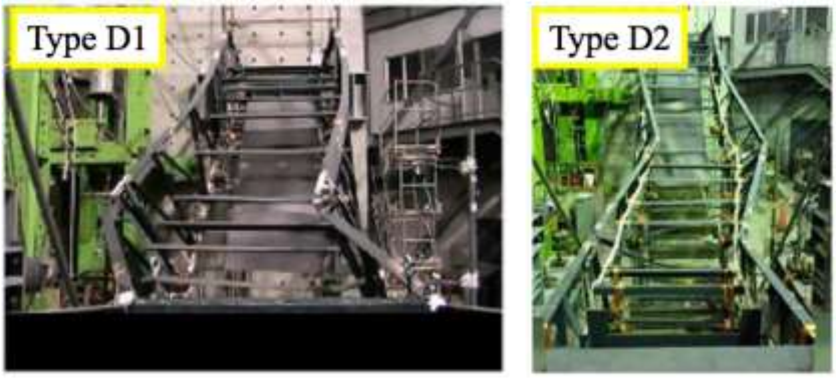


Figure 12 Deformation state of the type D1 and D2 escalator truss

The findings obtained from experimental tests are summarized as follows and all the results obtained in the tests are shown in Table 4;

1) As shown in Figure 8, during the experimental tests, forced displacement amount was given to all specimens up to about 200 mm (equivalent to about 1/15 of story drift angle), but the truss structure and beam structure never dropped. Cracks and fractures in the welds of the parts and large deformation of the lower bent potion other than the upper chord material and the intermediate part diagonal material were not observed. As for the beam structure, the moment generated at the lower bent portion was the maximum, and deformation occurred at the lower bent portion of the escalator.

2) From Figure 8, if the deformation in the horizontal axis direction is within 20 mm, it is found that escalator trusses behave elastically, the dimensions are almost restored to the original size after unloading. In addition, as shown in Figure 8 and Table 4, when the forced displacement was given up to 40 mm and then unloaded, the trusses restored about 20 mm in the horizontal axis direction. Moreover, when forced displacement is applied to about 200 mm, they restored from about 31 mm to 45 mm after unloading.

Table 4 Experimental tests results

Item		Type of escalator truss structure							
		Type A	**Type B1**	**Type B2**	**Type C1**	**Type C2**	**Type D1**	**Type D2**	**Beam structure**
Maximum deformation member		Upper chord material	Diagonal members		Upper chord material		Upper chord material		-
Maximum deformation point		Lower bent portion	Inclined portion		Lower bent portion		Inclined portion		Lower bent portion
At maximum load	**Load value**	509 kN	446 kN	450 kN	384 kN	361 kN	453 kN	437 kN	455 kN
	Displacement	20.4 mm	21.3 mm	37.7 mm	19.7 mm	18.6 mm	17.8 mm	15.4 mm	40.3 mm
At maximum displacement	**Load value**	76.3 kN	144 kN	155 kN	51.1 kN	57.1 kN	46.0 kN	52.8 kN	131 kN
	Displacement	204 mm	186 mm	186 mm	191 mm	195 mm	197 mm	194 mm	195 mm
Restoration dimension after unloading	**At 40 mm**	18.3 mm	20.8 mm	30.8mm*	19.7 mm	20.0 mm	20.2 mm	20.9 mm	29.1 mm
	At 80 mm	26.5 mm	30.2 mm	———*	25.9 mm	28.6 mm	25.6 mm	26.3 mm	38.5 mm
	At maximum displacement	40.3 mm	42.2 mm	45.3 mm	37.9 mm	39.5 mm	31.5 mm	32.0 mm	60.6 mm

* In the test for Type B2 escalator truss, buckling deformation appeared on the member at the forced displacement around 40 mm, so it was unloaded only when the forced displacement was 60 mm.

4 RELATIONSHIP BETWEEN FORCED DISPLACEMENT AND OVERLAP ALLOWANCE

It was confirmed that some dimensions are elastically restored in the horizontal axis direction after unloading in the full-scale experimental tests using trusses with a rise of 3,000 mm. From this result, considering the restored dimension of the trusses after unloading, we proposed the calculation formula of the margins for clearance and overlapping allowance required to prevent falling off.

(1) Calculation formula of overlapping allowance for one end fixed state

In the fixed state at one end, the forced amount of displacement is expressed by the equation $\sum \gamma \cdot \mathrm{H} - \mathrm{C}$. When the restored dimension δ assumes at least 20 mm from the experimental results, the length of overlapping allowance B is given by the following equations.

In the case of $\Sigma\gamma H - C \leqq \delta = 20$ $\quad \Delta\varepsilon = 0,\ B = \Sigma\gamma H + \beta$

In the case of $\Sigma\gamma H - C > \delta = 20$ $\quad \Delta\varepsilon = \Sigma\gamma H - C - \delta,\ \ B = \Sigma\gamma H + \beta + \Delta\varepsilon = 2\Sigma\gamma H - C$

(2) Calculation formula of overlapping allowance for both end non-fixed state

In the non-fixed state at both ends, the amount of forced displacement is expressed by the equation $\sum \boldsymbol{\gamma} \cdot \mathbf{H} - \mathbf{C} - \boldsymbol{D}$. When the restored dimension δ assumes at least 20 mm from the experimental results, the length of overlapping allowance B is given by the following equations.

In the case of $\Sigma\gamma H - C - D \leqq \delta = 20$ $\Delta\varepsilon = 0$, $B = \Sigma\gamma H + D + \beta$

In the case of $\Sigma\gamma H - C - D > \delta = 20$ $\Delta\varepsilon = \Sigma\gamma H - C - D - \delta$,

$$B = \Sigma\gamma H + D + \beta + \Delta\varepsilon = 2\Sigma\gamma H - C$$

Where,

- γ : Story drift deformation angle for design given by building structure designer
- H : Rise of escalator
- Δ : Restored dimension
- Δε : Plastic deformation amount of truss
- B : Length of overlapping allowance (margin length)
- C : Length of clearance (gap) at one end to be calculated
- D : Length of clearance (gap) on the opposite side from the one end to be calculated

5 CONCLUSION

(1) Experimentally examined by using full-size escalator trusses without any internal equipment and so on. Truss structure Type A, Type C and Type D showed deformation of upper chord material, and in the Type B tests, intermediate diagonal member deformed. In addition, in the beam structure, deformation occurred at the lower bent portion. As a result, the truss structure and beam structure never dropped due to breakage of their member or excessive deformation.

(2) Considering the reinforcement effect by the internal equipment of the escalator, it can be expected that the truss structure and beam structure has sufficient strength against escalator falling off from the support angle of the building by compression effect during severe earthquakes.

(3) In order to prevent the escalator from coming off against severe earthquakes, even when the calculated lateral displacement of the beam of the building supporting the escalator becomes the maximum value, the length of overlapping allowance is necessary to have a sufficient length that the escalator's support angle does not release from building structure beam.

(4) When the clearance between escalator and building beams supporting the escalator is the minimum, a clearance must be provided so that the escalator and the building beam do not collide. In case of collision, it is necessary to verify the strength of the truss of the escalator.

Since there was little technical knowledge about the deformation of the truss when the escalator collides with the building beam, there were technical problems in the strength evaluation method by the time of this investigation were carried out. Based on the results obtained in this full-scale experiment, it was conceivable to examine more detailed strength evaluation method. As a result, based on the results obtained in this experiment, we add that August 3, 2016 announcement of revised Notification No. 1046 of Ministry of Land, Infrastructure and Transport Notification No. 1046 was promulgated.

6 ACKNOWLEDGMENTS

With the support of the Ministry of Land, Infrastructure and Transport, Tokyo Denki University and the Japan Elevator Association organized a committee. In this committee, experts in construction and mechanical systems, Housing Bureau of the Ministry of Land, Infrastructure and Transport, National Institute for Land and Infrastructure Management and Building Research Institute of the Ministry of Land, Infrastructure and Transport, and Japan Building equipment and Elevator Center (BEEC) attended. Especially, authors greatly appreciate the cooperation of the Building Research Institute that provided useful technical guidance. Finally, authors thank Mr. Nariya and Mr. Tanaka of the former Tokyo Denki University graduate students for their dedicated cooperation in carrying out the experimental tests.

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BIOGRAPHICAL DETAILS

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MLIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MLIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Mr. Motoo Shimoaki was a managing director of the Japan Elevator Association (JEA) about ten years from 2008 to May 2018. In JEA, he served as a member of the ISO/TC 178 Japanese committee and the lifts and escalators committee to develop a Japanese industrial standard (JIS) that is consistent with international standards. And with prof. Satoshi Fujita of Tokyo Denki University, JEA carried out several projects of MLIT. In addition, as one of the activities of JEA, when a large earthquake occurs in Japan, the damage situation of the lifts and escalators is investigated each time, and it is reflected in the seismic design guideline of the lifts and escalators. Before JEA, he has extensive experience at Mitsubishi Electric Corporation as a mechanical engineer and experience as a president of the Mitsubishi Elevator Company Asia in Thailand.

Lift Engineering Design Challenges from the Postgraduate Programme Perspective

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Keywords: lift (elevator) engineering, systems engineering, postgraduate programme, safety standards, design, friction, safety gear

Abstract. This paper describes the background and concept of a postgraduate lift engineering programme, comprising an MSc Lift Engineering and PhD/ MPhil, aimed at those involved in lift engineering and related fields. The MSc in Lift Engineering integrates a systems engineering approach with other modules such as a study of global codes and standards, contract management, elective modules and a dissertation. Solutions to a design challenge arising from the results of safety gear drop tests are drawn from the systems engineering approach of the learning materials and in the context of an earlier MSc dissertation. Newly presented data from drop tests is analysed to provide information on the variation of safety gear friction with rubbing speed and this is compared with the results from earlier dissertation research work.

1 INTRODUCTION

In view of the present world-wide interest in the development of safe and cost-effective means of vertical transportation the importance of engineering education for technical staff employed within the Lift (Elevator) Industry cannot be overestimated. The principles underlying Lift Engineering involve a broad range of subjects including Electrical and Electronic, Mechanical, Civil and Production/ Manufacturing Engineering. A successful academic programme in Lift Engineering should therefore integrate those areas [1, 2].

This paper presents an academic postgraduate programme which comprises a Masters level postgraduate course combining practice, learning and research in lift (elevator) engineering. The programme is described in section 2 elaborating earlier work [10]. The link between programme content and research is illustrated by the examination of selected topics in section 3. The systems engineering approach to the behaviour of a lift during safety gear operation is extended by examining research work undertaken as part of the programme. This research provides the context for further research which is presented here.

2 THE LIFT ENGINEERING PROGRAMME

2.1 MSc course structure and delivery

The Masters (MSc) course is composed of compulsory and elective/ designated taught modules, plus an independent, industry-based research study presented in the form of a dissertation [3]. The compulsory taught modules are concerned with Lift Applications Engineering, Codes and Standards and Management of Contracts, all of which are essential. Elective modules provide students with the opportunity to pursue their own specialization within the industry and currently include Lift Component Applications, Hydraulic Systems, Control Systems, Utilization of Materials, Dynamics and Vibrations, and Vertical Transportation Systems.

The MSc is delivered in a distance learning regime with students typically employed within the wider lift (elevator) industry. This allows the practice of their employment to inform their choice of elective modules and the direction of their research. The flexible structure of the course and distance learning regime of study minimizes time away from work and benefits both the employer and the employee.

In this regime the emphasis is on learning rather than teaching. The assessment structure of the MSc consists of numerous self-assessment questions (SAQs) in the learning materials to aid learning, through assignments posing design challenges or encouraging deeper understanding of an important aspect, to a case study module which combines assessment of lift applications engineering, codes and standards, and contracts management. In order to progress to the dissertation a student must achieve passes in each of the compulsory modules and two elective modules (at the first or second attempt).

The tutorial team is staffed and supported by a combination of experienced educational practitioners, together with experienced practitioners drawn from the UK lift industry. The tutors fulfil the role of facilitators of learning. Furthermore, the acquisition of the skills of self-learning is a primary and specific aim of the provision. The tutorial team in collaboration with the lift industry has been involved with the design, development and operation of a Distance Learning course in Lift Technology since 1983. Thus, learning materials for the MSc course have been designed and are continuously revised for use by distance learning students building on and developing from the 35 years of operation of the distance learning provision.

2.2 MSc dissertation and research projects

Having achieved a pass for all the required compulsory and elective modules, the student is required to undertake advanced independent study leading to the MSc dissertation. The research project forms an integral part of the course and gives students an opportunity to conduct an independent study making use of the skills and knowledge acquired elsewhere in the course. Research topics chosen typically reflect students' interests and draw on the learning from the modules undertaken. Each candidate is required to propose and justify a research topic as a subject of the dissertation.

The dissertation module involves the identification of research objectives, the selection of appropriate methods with regard to the research problem, the presentation of the research work plan and an initial review of relevant literature. A research proposal, addressing these elements, must be submitted to the tutorial team for approval before the student can proceed with the research work. Further development of the research proposal might be required to meet the needs of Masters level research and to be approved.

Subsequently the student manages their own time and activities to bring the project to a successful conclusion. Students have access to specialized literature and research resources at the University. The students maintain a chronological record of the work undertaken in pursuit of the project which is periodically submitted to their tutors. This forms an important element compensating for the reduced face to face contact between student and tutor as compared with a similar, but full time student.

Once completed, the submitted dissertation is assessed by the tutorial team including a viva voce. It is not unusual for the path of the research to diverge from that originally intended. Indeed, often objective research might not deliver the outcomes expected. It would be expected that the student would be able to justify such changes. Successful completion of the dissertation module completes the MSc in Lift Engineering.

Over recent years over seventy successful projects have been completed and MSc dissertations submitted. They cover a broad range of topics and reflect both the students' interests and the industry needs demonstrating strong relationship between practice and theory across a number of lift (elevator) technology areas. Two book volumes with reviews of the MSc dissertations have been published by Elevator World [4,5]. The topics cover a broad range of problems such as the effect of building sway on elevator ropes, power comsumption, firefighting and evacuation, usage and utilizing lifts for the differently abled people, safety gear performance, code requirements for interfaces between building systems and elevator systems, accidents involving luggage trolleys and/or shopping carts on escalators.

2.3 Research degree programme

The research programme provides an opportunity for the MSc graduates to continue their studies towards higher research degrees (PhD/MPhil). The programme environment offers an opportunity for students to network with a variety of contacts through research seminars and conference events.

Each academic year commences with the annual Symposium on Lift and Escalator Technologies organized in conjunction with the Chartered Institution of Building Services Engineers (CIBSE) Lifts Group and the Lift and Escalator Industry Association (LEIA). This event provides opportunities for students, practitioners and engineers from industry and academia worldwide to network and discuss the latest training, education, research and innovation developments. The symposium event is now in its 9th edition and is taking place from 19th to 20th September 2018.

3 SELECTED TOPICS

3.1 Background

The issue of slowing and bringing the lift car safely to rest is one of the most important problems in the design of a lift installation. This problem is addressed in the MSc syllabus [3] in the context of the traction drive system and the relationships between braking, drive control and traction are comprehensively treated throughout the course learning materials.

This involves the electromechanical brake and the entire range of situations with which it might have to deal, including normal and emergency conditions, considering the interfaces and linkages between the brake and the control systems, and between the brake and the lift car. In accordance with EN 81-20:2014 [8], the electromechanical brake alone must be capable of stopping and holding 125% of the rated load. The lift system will be required to stop under the action of electromechanical braking if there is an unconventional event such as the opening of the landing door whilst the lift is in motion, or an interruption of the power supply, for example [1].

However, the discussion of the issues above is predicated upon the assumption that the traction system remains intact and that deceleration of the system is achieved by a braking torque applied to the traction sheave. Thus, the dynamics of the stopping / arrest of the lift car may be limited by the available traction. Therefore, it is necessary to investigate the ultimate systems for arresting uncontrolled downwards motion which consist of the following elements:

- an overspeed governor set to trip at a pre-determined speed at least 115% of rated speed. An electrical trip should de-energise the drive and engage the electromechanical brake before the car speed reaches this tripping speed and

- a safety gear located on the car which will arrest a free-fall or overspeed in the down direction.

Also suitable devices are required to arrest an overspeed in the up direction (or to ensure that the speed does not exceed that for which the counterweight buffer is designed) or any unintended movement with doors open in either direction with their own detection and actuation means.

Figure 1 shows the main components of a system for emergency arrest in the down direction [1]. An overspeed governor located above or in the upper part of the hoist way is connected to the safety gear system on the car by the governor rope. The governor rope is a complete loop, with both ends terminated on the safety gear system on the car, after passing around a loaded tensioning pulley in the pit. The two basic types of mechanical overspeed governor (rocking arm and pivoted bob-weight types) are shown in the diagram together with the three basic types of safety gear - instantaneous (type A) either cam type or captive roller, and progressive (type B). On the car, the governor rope is terminated at the top of the car and connected to the safety gear via a safety gear operating rod.

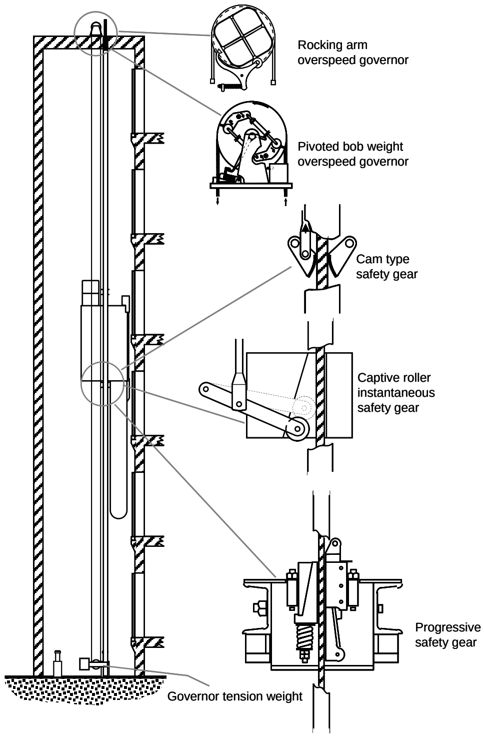


Figure 1 Safety gear – car system [1]

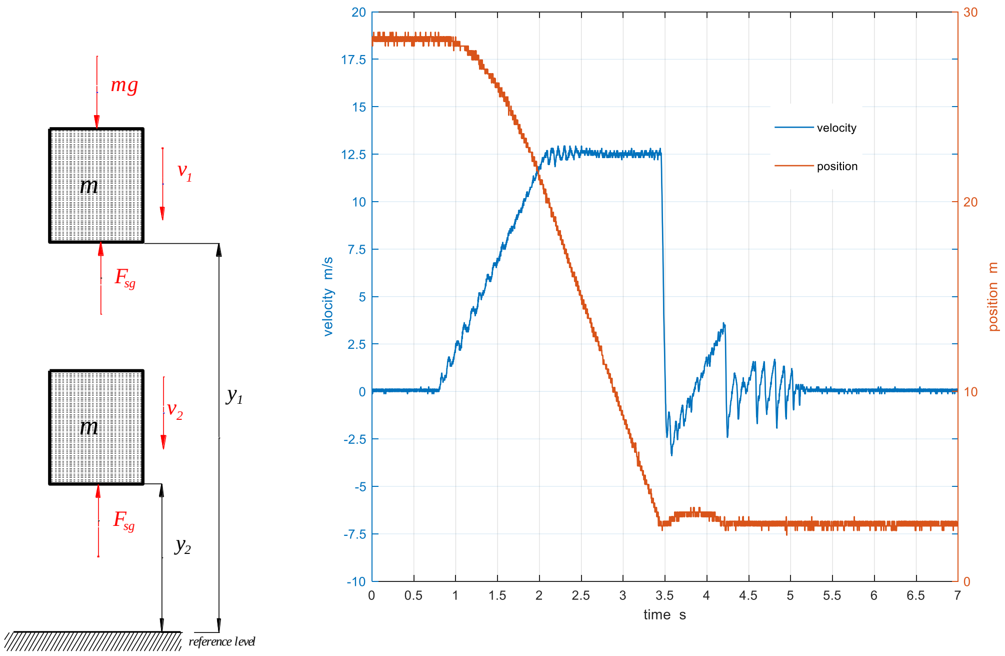
3.2 Lift car - safety gear performance analysis

Consider a simplified diagram of the car – safety gear interaction shown in Figure 2(a). In the scenario considered here the car suspension failure is assumed. The car is represented by a rigid body of mass *m* acted upon by the safety gear braking force F_{sg}. If at the time instant t_1 the car has a speed of v_1 and at the time instant t_2 the speed is v_2 the application of the principle of work and energy [6] yields

$$\frac{1}{2}mv_1^2 + mgy_1 - F_{sg}\Delta y = \frac{1}{2}mv_2^2 + mgy_2 \tag{1}$$

where $\Delta y = y_1 - y_2$ is the distance travelled by the car when being slowed down by the safety gear actions and g is the acceleration of gravity (9.81 m/s^2).

Figure 2(b) shows the results (velocity, position plots) of a drop test to examine the performance of a safety gear device to be installed in a lift car of mass m = 10270 kg [7]. In Figure 2(c) the mean acceleration of the mass is shown. It is evident from the test results that during the test the free fall of the mass is arrested at the time instant t_1 ($\approx 2.1\,\mathrm{s}$) and then over the time interval $\Delta t = t_2 - t_1 \approx 3.45 - 2.1 = 1.35\ \mathrm{s}$ the car continues to descend at a near constant speed (of about 12.5 m/s). Thus, the braking force developed by the safety gear is of inadequate magnitude, and it is just large enough to balance the car weight ($F_{sg} \approx mg$). Thus, the safety gear needs to be re-designed.



(a) **(b)**

Figure 2 Safety gear action (a) simplified model; (b) test results: velocity - position plots

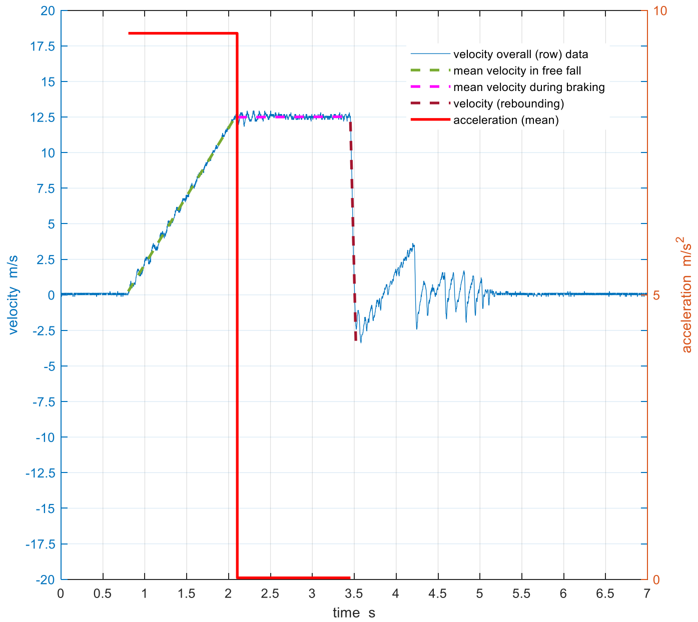


Figure 2 (c) Safety gear velocity – acceleration plots

The required braking force to decelerate the car from v = 12.5 m/s to rest can be determined from (1) by setting $v_2 = 0$ so that the following equation is obtained

$$\frac{1}{2}mv^2 + mg\Delta y - F_{sg}\Delta y = 0 \tag{2}$$

The braking force is then expressed as

$$F_{sg} = \frac{\frac{1}{2}mv^2 + mg\Delta y}{\Delta y} \tag{3}$$

By using $\Delta y = v^2/2a$ in Equation 3, where a denotes the deceleration, and setting the deceleration as a = 0.6 g_n (the nominal deceleration required in EN 81-20 [8]) the required safety gear braking (friction) force is determined as 161.2 kN. During the test the braking force applied was approximately $F_{sg} \approx mg$ = 100.75 kN. The required increase is very significant and could potentially be achieved by various means explored below.

For a progressive (Type B) safety gear, the braking forces were investigated in one MSc dissertation [4, 9] extracting data from drop test results of a family of safety gears and comparing these with the literature and other safety gears. The braking force is generated by the interaction of the braking surfaces (gibs) of the safety gear and the guide rail. To a first approximation, this braking force for a single safety gear can be modelled as:

$$F_{sg} = N\mu R \tag{4}$$

where N is the number of braking surfaces (2 in the case of a single gib to each side), R is the reaction force between each braking surface (generally produced by springs and the guide rail and μ is the coefficient of friction between the sliding surfaces.

Thus, in looking to increase the braking force of the safety gear, there are three avenues to investigate.

- Increasing the number of braking surfaces (gibs), N, along with reaction springs etc. However, to increase the number of braking surfaces in each safety gear would be a significant design change as it would also increase the number of reaction springs and hence the clamping force for which the safety gear housing must be designed and the stopping force transmitted through the safety gear housing.

- Increasing the coefficient of friction, μ. However, μ is determined by the selection of materials for the safety gear gibs and machined steel guide rails. A significant increase could be made by changing the materials used e.g. from conventional hardened steel gibs to a material as used in automotive brake pads and by changing the design. This would also result in significant increase in the stopping force to be transmitted through the housing requiring a review of the safety gear design.

- Increasing the reaction force (generated by springs), R, consistent with the design of the safety gear e.g. limitations from the strength of the safety gear housing, heating of the braking surfaces, and avoiding excessive pressure and damage to the sliding surfaces which would tend to limit the reaction force used.

Within the context of the MSc in Lift Engineering, these potential changes would all require significant design changes of the safety gear which could be further considered in the Lift Component Applications module of the MSc in Lift Engineering.

3.3 Variation of coefficient of friction with speed

A further drop test result was examined as shown in the speed plotted against time Figure 3. This shows two stages:

- The free-fall of the test mass shown in the light blue trace "acceleration" in Figure 3. During this period, speed increases linearly with time as expected but with a gradient of 9.5385 m/s^2 as shown by the linear trend-line fitted to this part of the speed plot. The extent to which this is less than the acceleration due to gravity, 9.8067 m/s^2, is presumed to be related to friction of the guidance system and other loses.

- The stopping phase when the safety gears grip the guide rails and bring the test mass to rest shown in the dark blue trace "deceleration" in Figure 3. During this phase, the reduction in speed is clearly not linear – the acceleration is shown by the gradient of the plot which increases steadily from tripping to be a maximum as the speed reduces to zero. This is evidenced by a trend-line with second order polynomial fitting the speed graph extremely well.

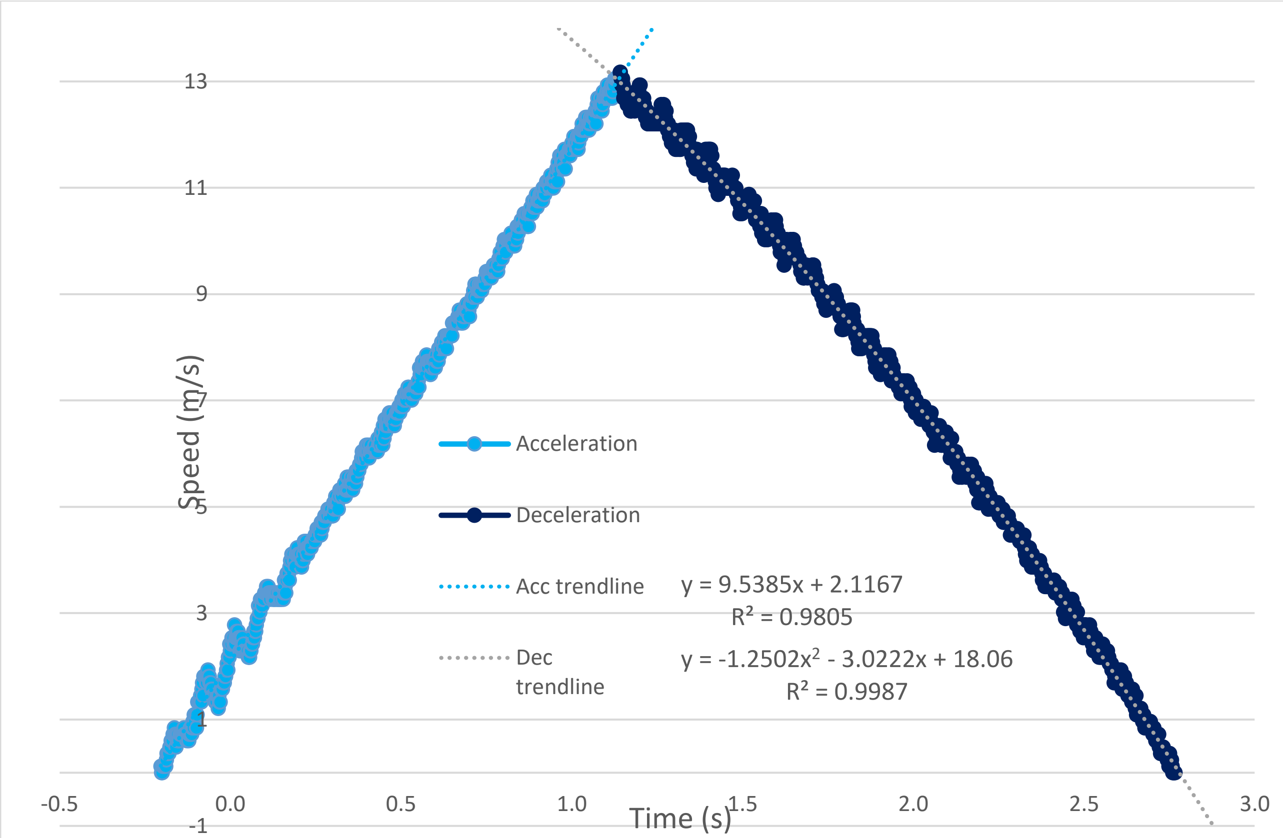


Figure 3 Drop test speed profile

In equations 1, 2 and 3, the safety gear force, F_{sg}, was treated as constant or an average over the stopping phase. Since for the free-fall of the test mass, m, it is clear that the acceleration, a, varies then it is clear that safety gear force varies and can be found by taking the slope of the speed plot:

$$F_{sg} = m\left(g_n + \frac{dv}{dt}\right) \tag{5}$$

Using equation 3 to calculate a value of the coefficient of friction, μ, allows this to be plotted against sliding speed as shown in Figure 4.

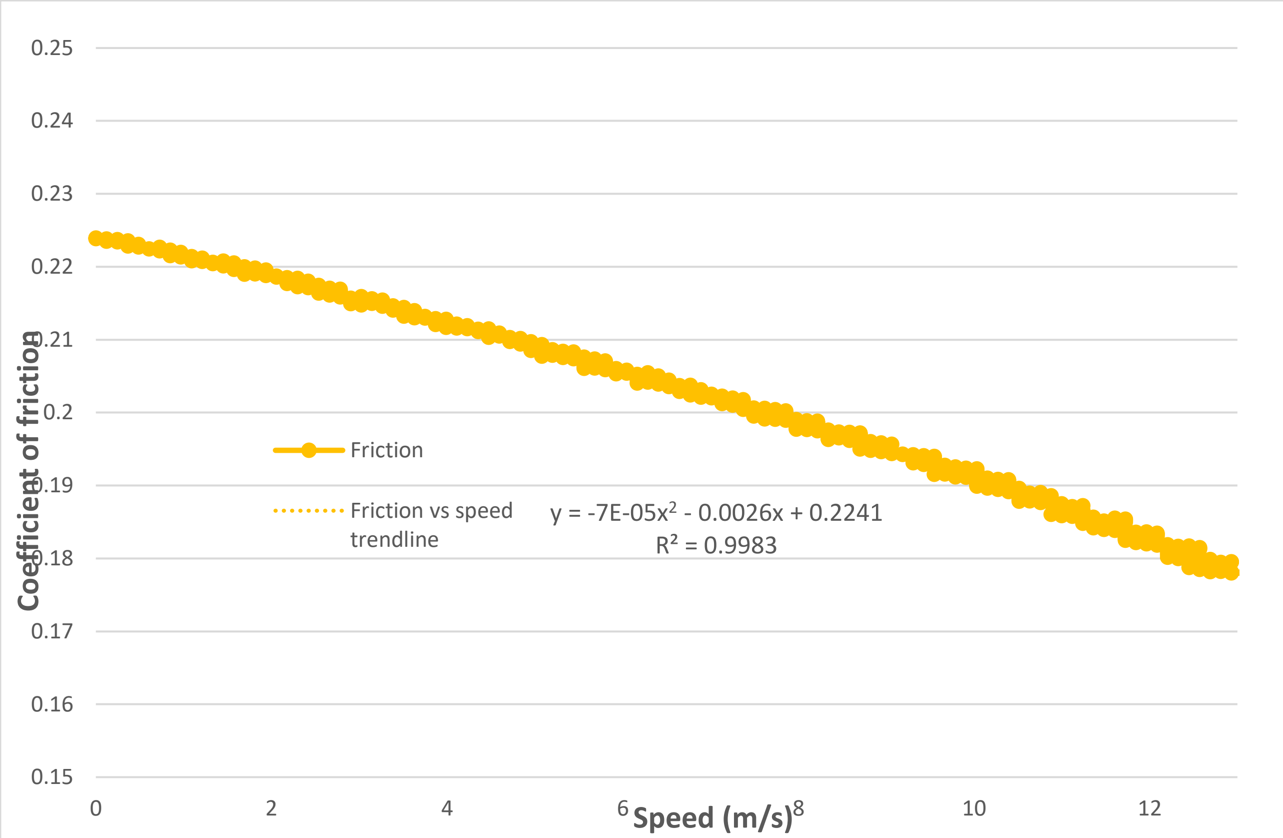


Figure 4 Coefficient of friction vs sliding speed

Figure 4 shows a clear reduction in the coefficient of friction as sliding speed increases; with a 20% reduction from zero speed to 13 m/s. As such, it can be seen to be much less speed-dependent than the safety gears studied as part of the MSc dissertation [4, 9], especially over the very wide speed range of the safety gear. Indeed, one of the design objectives of a high-speed safety gear of this type is to limit the speed-dependence of the braking force to within acceptable limits as in this case.

Variations in the value of μ have been documented at least as far back as 1865 with the coefficient of friction for railway brakes being lower at higher sliding speeds and also dependant on the reaction force *R*. These dependencies were recognised in the lift literature, were implied by numerous progressive safety gear drop test results, and were studied by an MSc dissertation [4, 9]. The MSc dissertation studied this speed dependence where the variation of the coefficient of friction with rubbing speed for a single gib/ guide rail interaction was modelled as:

$$\mu = \mu_0 e^{-cRv} \tag{6}$$

where v is the sliding speed, μ_0 is the coefficient of friction when $v = 0$, R is as before, c is a constant.

Such a curve would not be as good a fit as the second order polynomial trend-line shown in Figure 4.

This research project investigating variations in friction arose from a practical problem encountered previously with the operation of safety gears. It was undertaken partly to investigate aspects of safety gear performance and so was typical of many MSc dissertation projects as it was based on a study of application design. The project yielded not only a useful academic result but also a practical result; one of the outcomes of the study was that the safety gear design studied had its nominal load increased for use at lower tripping speeds since the research evidenced higher braking forces at lower speeds.

The research project also informed the study of codes and standards which must balance ensuring a minimum braking force at tripping with limiting the maximum acceleration. For this reason, EN 81-20 specifies average the retardation for progressive safety gears in terms of free fall of the car with rated load to lie between 0.2 g_n and 1 g_n. Whether the margin of 0.2 g_n is sufficient in all cases is a moot point. So issues which arise from the selection of safety gear is the selection of safety gear and the maximum allowed variation in empty car weight (as has been discussed elsewhere).

4 CONCLUSIONS

The Lift Engineering provision has been developed to integrate three key elements: practice, learning and research. The programme includes a modular MSc taught through distance learning. The taught modules cover a broad range of areas relevant to the theory and practice in the field of lift technology. The student then undertakes an advanced independent study leading to the MSc dissertation.

The relationship between practice, learning and research has been illustrated with an example of a practical design problem on uncontrolled movement downwards, the treatment in the course materials and theory under-pinning the design of safety gears informed by a previous MSc dissertation. Data from more recent safety gear tests has been examined in the context of earlier MSc dissertation work.

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BIOGRAPHICAL DETAILS

Nick Mellor has worked for the UK’s Lift and Escalator Industry Association (LEIA) as Technical Director and Managing Director since 2012 and has been in the industry since 1992. Nick was in the inaugural cohort of the MSc in Lift Engineering at Northampton. More recently, as an Associate Lecturer, he has tutored on the MSc. He sits on the BSI lifts committee MHE/4, working on the development of British Standards in the lift and escalator fields, and a number of CEN TC10 and ISO TC178 working groups including those for lift operation in the event of fire.

Stefan Kaczmarczyk is Professor of Applied Mechanics and Postgraduate Programme Leader for Lift Engineering at the University of Northampton. His expertise is in the area of applied dynamics and vibration with particular applications to vertical transportation and material handling systems. He has been involved in collaborative research with a number of national and international partners and has an extensive track record in consulting and research in vertical transportation and lift engineering.

Rory Smith has over 49 years of experience in all aspects of the lift industry including sales, installation, maintenance, manufacturing, engineering, research & development. He has worked for ThyssenKrupp Elevator for the last 23 years. Prior to becoming involved in ThyssenKrupp’s Internet of Things, he was Operations Director, ThyssenKrupp Elevator Middle East. His scientific interests include, operations management, high rise - high speed technology, ride quality, traffic analysis, dispatching. To date he has been awarded numerous patents in these areas and has many pending patents.

Lift Traffic Analysis for a Proposed Inner-City Development. A Comparison of the Lift Control Algorithms Considered

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Keywords: controls systems, control algorithms, traffic analysis, hall call allocation, HCA, next car available, group control system, NCA, estimated time of arrival, ETA, manual calculation, analytical method, simulation

Abstract. This account commences with an original enquiry regarding a proposed mixed development in Nottingham and the results presented to the client. The initial enquiry indicated the building will be subject to heavy mixed lunch time traffic. It was surprising to note the newest and most complex system, Hall Call Allocation, failed to satisfy the client's and the BCO traffic requirements [3]. This investigation set out to examine why one control system appeared to perform better under certain conditions. Alongside academic research, traditional mathematical calculations and simulations were used to explore and test the differences. This paper outlines and examines three generic group control systems and explores the basic concepts and differences of each system considered for the project. This investigation also briefly reviews calculation and simulation and the differences these make to the way the control algorithms are considered and treated.

The results of the various pre-design simulations, subsequent research and conclusions were somewhat unexpected. The differences were also surprisingly subtle.

This paper briefly follows the research of the "Technical Report" prepared in support of the author's application for C.Eng. registration earlier this year.

1 INTRODUCTION

This investigation originates from an on-going project - a Developer's and Architect's vision. The Report develops from the initial assessment and analysis Abbacas provided to a developer in 2016. It focuses on the different lift traffic performances provided by the various group control systems investigated.

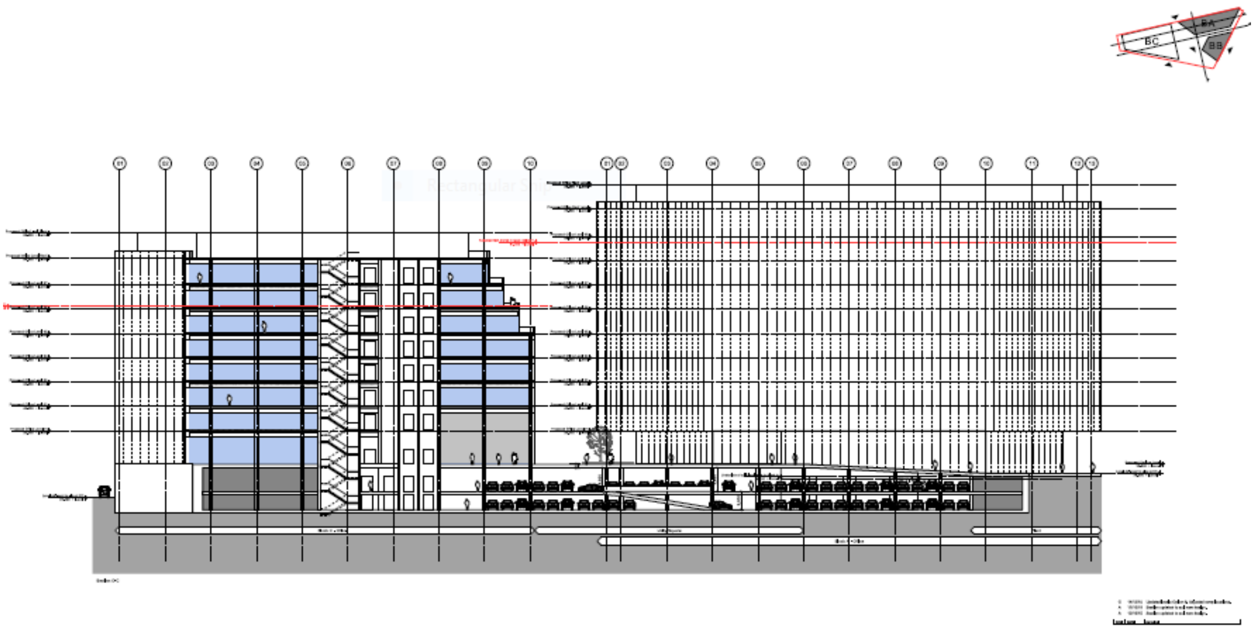


Figure 1 East Elevation of the proposed development

The proposed development presents a particularly challenging commission as it consists of three multi-storey blocks, each with different layouts, floor areas, floor numbers and various classes of accommodation and use, including: office, retail and hotel accommodation. Each block rises independently from a common area on the ground floor, with two car-parking levels below. This creates patterns of access, circulation and egress that are both complex and difficult to calculate.

There are a multitude of control systems in the market place, from the major lift manufacturers and independent controller manufacturers. Each comes with a claim of improving performance. Each one has it adherents and critics! This paper set out to briefly explore the differences between the group control systems and the reason for the difference in their responses and briefly follows the steps taken in the full Technical Report.

2 UNDERSTANDING PASSENGER MOVEMENT AND LIFT RESPONSES

There are several conditions of passenger traffic a lift control system must contend with.

Apart from being idle, there are four basic traffic conditions a lift system may experience:

2.1 Light Random Traffic – balanced interfloor

No dominant direction of travel. Light demand – less than 3 x passengers for each available car [11].

Generally found between peak periods, it normally consists of a relatively equal number of up and down journeys to the main and intermediate floors. Several cars may be parked or unused.

This is of no concern to the lift designer, as it places little demand on the control system.

2.2 Up Peak – uppeak

The dominant direction of travel is upwards. Heavy demand - Cars are over 50% of capacity [11]

A typical uppeak can be found at start of work period. It is characterised by a gradual build-up of passengers to a maximum demand with a sharp decline. Whilst the whole period may last 30 - 60 minutes, it is common practice to size the lift group system on the busiest 5 minutes of the peak [2,9]

2.3 Down Peak – dnpeak

The dominant direction of travel is downwards. Heavy demand - Cars are over 50% of capacity [11]

A typical dnpeak can be found at the end of the work period. It is characterised by a steeper build-up of passengers to an uppeak demand and lasts a little longer, so 10 minutes is normally applied to this peak [1,2].

2.4 Mixed Peak –lunchpeak

No real dominant direction of travel. Heavy demand - Cars are over 50% of capacity [11]

Traffic flows in both directions to intermediate floors with common welfare & social facilities as well as the main floors. Unlike the other peak conditions, this may last for a couple of hours with more than one peak flow, in both directions, to deal with.

This has proved to be the hardest condition to predict and accommodate.

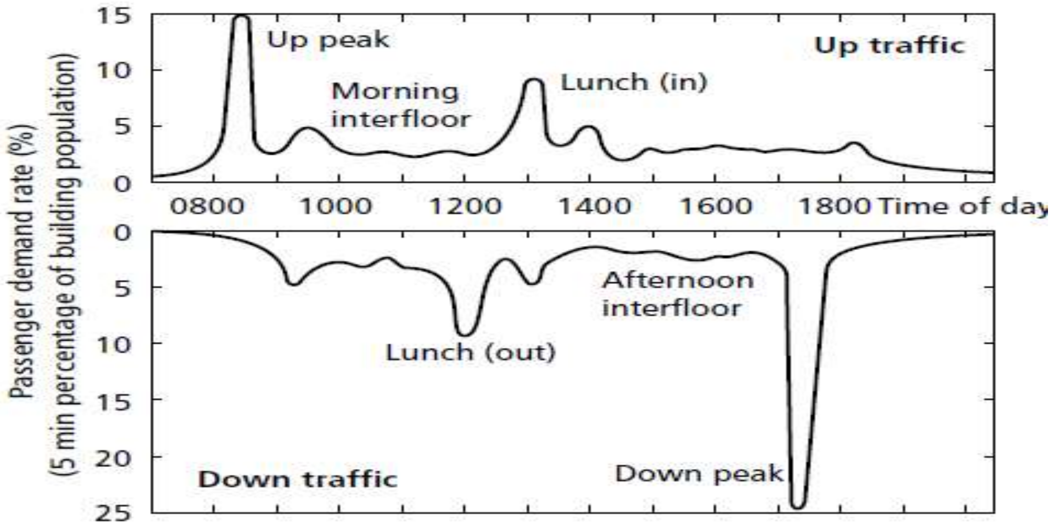


Figure 2 A classical view of passenger traffic in an office block (courtesy of CIBSE Guide D:2015)

3 BASICS OF TRAFFIC ANALYSIS

Understanding the basics of passenger movement and traffic analysis is essential, irrespective of the method used, whether it be an analytical mathematical or computer simulation.

There isn't enough time or space to go through the details and mathematics here, except to mention one equation, and this is the Round Trip Time. The RTT consists of many elements of a hypothetical average journey of a single lift car; starting from the main floor, where persons enter the building and distribute an average number of passengers (P) in one trip to a probable numbers of floors (S) up to the highest probable floor (H) and returning (non-stop) to the main floor (MT) [1,5]. This underpins all traffic calculations.

The RTT calculation contains all the elements in the theoretical trip as displayed in this graph. The RTT was originally expressed by Barney & Dos Santos in 1975.

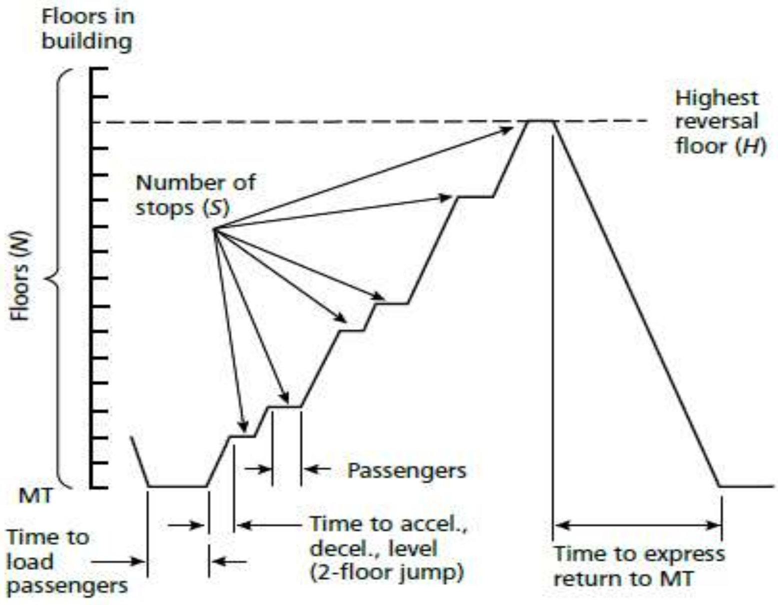


Figure 3 Round Trip Time in graphical form (courtesy of CIBSE Guide D 2015)

4 ANALYTICAL METHOD V SIMULATION

One of the steps of this journey was to review the methods of analysis and calculation. The simulation method highlighted the difference in control responses, but can the mathematics?

Whilst consistent, reliable and sophisticated, the basic manual calculations are simplistic and less flexible compared to the world of moving people. The standard calculations are based on a set of ideal conditions, using rectangular probability distribution; passengers arrive in a uniform rate, all travel up from the main floor, floor populations are proportional, floor heights uniform, etc. [4,6]

Simulation with its Poisson probability distribution, lends itself to more complex and multi-faceted situations with inter-floor traffic, differing floor populations, inconsistent floor heights, multiple access / egress floors and irregular passenger arrival [2].

Integers also play a part in the difference too; whereas calculation may use a decimal number (which creates part passengers), simulation only uses whole people [2].

The RTT is very useful when calculating the peak traffic conditions to or from the main floor. Although it can be extended to account for some of more complex situations; it cannot, however, handle them all. These conditions are better assessed with software driven iteration of General Analysis or Simulation, [8] both of which utilise Poisson passenger arrival.

Not only does having a good knowledge of the basic mathematics lead to a better understanding of the processes, but carrying out a manual calculation, allows a designer, to quickly establish which permutations are viable and worthy of further consideration before executing simulations [4]. It was clearly proven in this instance, as the manual calculations delivered a guide to “size” the lift systems and provided a starting point for the simulations.

The simulations fine-tuned the results, and in this instance, highlighted a variation between the different supervisory algorithms; a nuance overlooked by the mathematics!

The manual / spreadsheet method of calculation is by no means redundant as it provides the VT designer / specifier, as demonstrated in this project, with a quick assessment of the proposed system and a glimpse of the Quality of Service.

The analytical method also remains a good tool for projects with simple profiles, clearly defined peaks, undemanding inter-floor traffic and a single access floor. Due to the general size and design of buildings it is still well used in the UK.

Moreover, the mathematical method provides almost instant results, especially if executed in a spreadsheet; “what if” calculations are available with a single key press.

Unlike the mathematical method, a simulated solution takes time to deliver as the sequence needs to be repeated many times to achieve reasonably realistic results. The results are an average of all the simulated runs with each one based on a random seeding – the more simulations run, the more representative the resultant data will be [2].

5 REVIEWING THE CONTROL SYSTEMS

5.1 Conventional Group Control System – Next Car Available - NCA

The most modest of the 3 and in its simplest form is no more than a conventional Fully Collective Group Control System used on a simplex (one car) system, albeit interconnected with other lifts.

A lift car will be dispatched to the nearest hall call, in the direction it is travelling in, as long as it has capacity.

5.2 Estimated Time of Arrival - ETA

ETA is similar to the NCA (and to the passengers it appears identical) except the Hall Calls are prioritized, regarding the time a hall call has been registered. The supervisory group controller is constantly monitoring all hall calls and car positions; seeking the lowest Estimated Time of Arrival of a car answering a hall call.

5.3 Hall Call Allocation - HCA

A more sophisticated system that allocates cars and calls before passengers arrive at a lift car.

The group supervisory controller / dispatcher receives the passenger's intended designation from key pads (or encoded swipe cards) at each landing on arrival. The passenger is then directed to a lift car.

6 THE INVESTIGATION

After identifying and describing the different control systems, the next task was to compare their operation and performance. A simple method that was repeatable and could review all systems was required.

Following some detailed research, Dr Richard Peters explanation of the call degradation process in a Hall Call Allocation system [7] was selected to compare the effect of all three control systems.

6.1 Assessing the HCA

For this exercise, a simple algorithm, set to reduce Time to Destination only, was assumed.

Considering a 11-floor building (0 – 10) as in the chart below.

Two Hall Calls have been placed:

"A" is at level 6 wants to go to 2.

"E" is at level 5 descending to 0.

Car 1 is leaving level 10 with B, who is going to 8.

Car 2 is passing level 9 with C who is going to 5.

Car 3 is filling with 6 delegates on level 8 who are heading for level 1.

Car 4 is leaving level 4 with D who is going to 10

Table 1 Floors, passengers, car positions and hall calls

Flr	Hall Call (1)	Car 1	Car 2	Car 3	Car 4	Hall Call (2)
Direction		Down	Down	Down	Up	
10		B to 8				
9			C to 5			
8				6 pers to 1		
7						
6	A-to 2 s	☜ 20s	☜ 15s	☜ 10s		
5		25s ☞	20s ☞	15s ☞		E to 0
4					D to Top	
3						
2						
1						
0						

Each cell is equal to a floor level and represents 5 seconds transit time.

Passenger's journeys are not isolated; passengers affect each other. The effect on passenger's journeys are accounted for in the HCA calculation. This is known as the System Degradation Factor (SDF).

For clarity of this exercise, the SDF has been broken in to 2 sub components of inconvenience that passengers may experience within a journey:

- SDF1 - picking up other passengers.
- SDF2 - dropping off other passengers.

The HCA algorithm also includes the estimated time to the selected floor (TT) into its analysis.

Each possible journey is expressed as the Total Time Cost (TTC).

The TTC equals ETA + TT + SDF 1 + SDF2 and is expressed in seconds.

Table 2 Breakdown of Hall Call Allocation elements and times

Estimated Response Times in Seconds									
	Car 1			Car 2			Car 3		
Picking up	A	(A+E)	E	A	(A+E)	E	A	(A+E)	E
ETA	20	25	25	15	20	20	10	10	15
Transit	20	35*	25	20	35*	25	20	35*	25
SDF1 - Pick up	0	20	0	10	20	10	60	130	60
SDF2 - Drop off	10	10	10	10	10	0	60	130	60
TTC	50	90	60	55	85	55	150	305	160

*If A + E were travelling together in the same lift car the total transit time will be reduced. In this instance by 10 seconds (2 x 5s floors 4 to 3).

Table 3 The Total Time Cost of each car and effect on the intended passengers

For A to travel from 6 to 2:	For E to travel from 5 to 0:
Car 4 – not applicable as it has no effect.	Car 4 – not applicable as it has no effect.
Car 3 – 10 + 20 + 120 = 150 s.	Car 3 – 15 + 25 + 120 = 160 s.
Car 2 – 15 + 20 + 20 = 55 s.	Car 2 – 20 + 25 + 10 = 55 s.
Car 1 – 20 +20 + 10 = 50 s.	Car 1 – 25 +25 + 10 = 60 s.

6.2 The Decision

With the lowest Total Time Cost, of 50s, the Despatcher allocates Car 1 to collect A.

Car 2 has the lowest Total Time Cost, of 55s, and will be dispatched to collect E.

6.3 Assessing the Total Time Cost of the three systems

Applying the HCA analysis to the other systems.

Although the NCA and ETA do not assess the total time effect of their algorithms, the process of answering hall calls does affect the response and journey times.

The NCA despatcher makes no account of time and only looks for the nearest car in its direction.

The ETA despatcher only accounts for the Estimated Time of Arrival.

To compare we need to apply the SDF and TT to the ETA and the SDF, TT and ETA to the NCA.

Table 4 Expressing the TTC of each control system

	Pick up A – Travel from 6 to 2		Pick up E – Travel from 5 to 0	
	Car	**TTC**	**Car**	**TTC**
NCA	Car 3	10+20+30+60+60=150s	Car 3	15+25+40+60+60=160s
ETA	Car 3	10+20+30+60+60=150s	Car 3	15+25+40+60+60=160s
HCA	Car 1	20+20+0+10=50	Car 2	20+25+10+0=55

From the table 4 we note:

To pick up A:

- With the lowest arrival time, the ETA will also select car 3. SDF = 150s
- As it is the nearest car above, the NCA will select car 3. SDF = 150s
- With the lowest calculated TTC, the HCA selects car 1. SDF = 50s.

To pick up E:

- With the lowest arrival time, the ETA will also select car 3. SDF = 160s
- As it is the nearest car above, the NCA will select car 3. SDF = 160s
- With the lowest calculated TTC, the HCA selects car 2. SDF = 55s.

In both instances the HCA is beneficial to its passengers.

Although this is very simplistic, it clearly demonstrates the efficacy of the HCA system.

So, why doesn't the HCA surpass the other systems in all conditions?

7 A CLOSER ANALYSIS – USING SIMULATION

Considering Peters [7] example again. Running Step Profile simulations on the most onerous of the buildings, Block C, provided a more detailed view of what was actually happening.

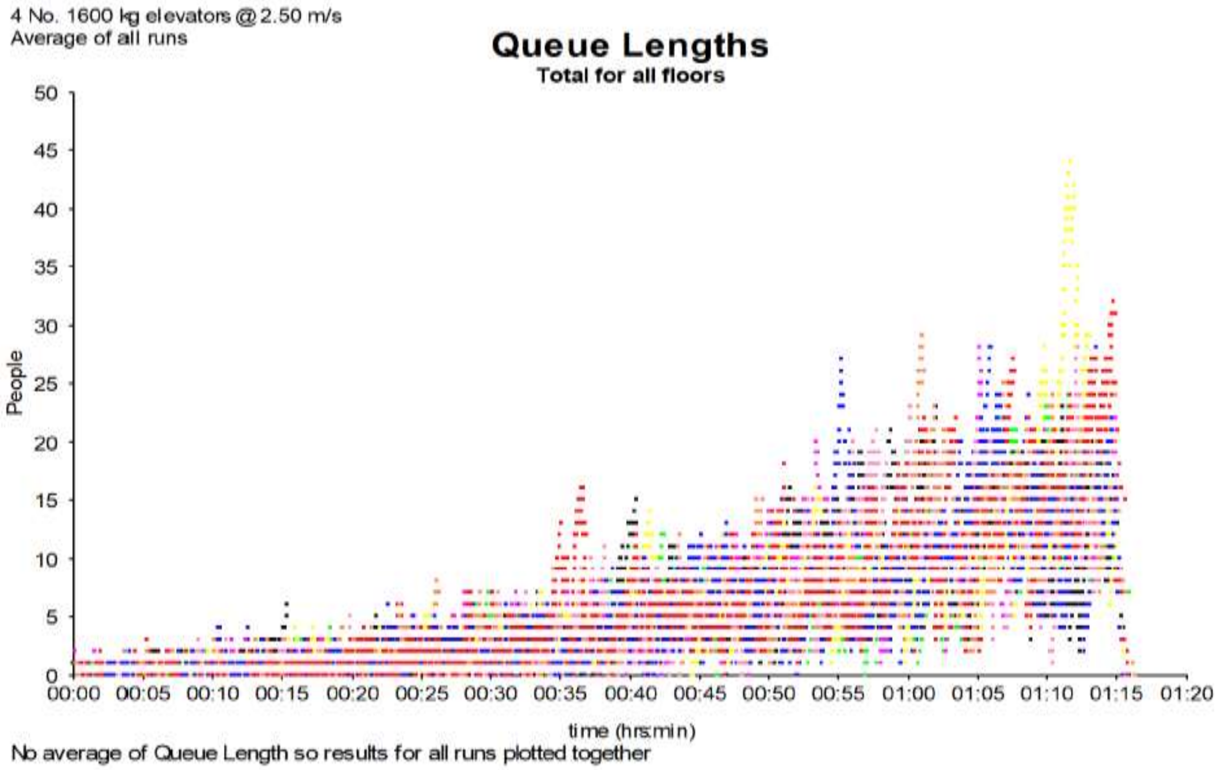
A Step Profile increments the number of arriving passengers, placing an increasing demand on the lift system. The number of persons is increased every 5 minutes until the system becomes saturated (overloaded). Although this simulation used the same lift and building data, it is not essential as this is comparing one dispatching system against another, however, each comparison must use the same data set.

Initially, Elevate was set to assess a Lunch Time mix of 45% Up , 45% Down & 10% Inter-floor , as described in the BCO [3] and then the 40 %, 40%, 20%, to accommodate the client's brief.

Whilst many outputs and results are available from Elevate, Time to Destination, Queue lengths and Waiting Times, were selected. Moreover, Waiting times is a specific parameter in the BCO [3] requirements and an integral component of the original appraisal. Many people would prefer to be travelling, even with more stops, than standing around waiting. This is a personal and psychological factor. It is another subject and worthy of a separate study.

8 STEP PROFILE SIMULATIONS – (MIXED TRAFFIC 40%, 40% & 20%) –

8.1 Next Car Available



Graph 1 Elevate step profile for Next Car Available control algorithm

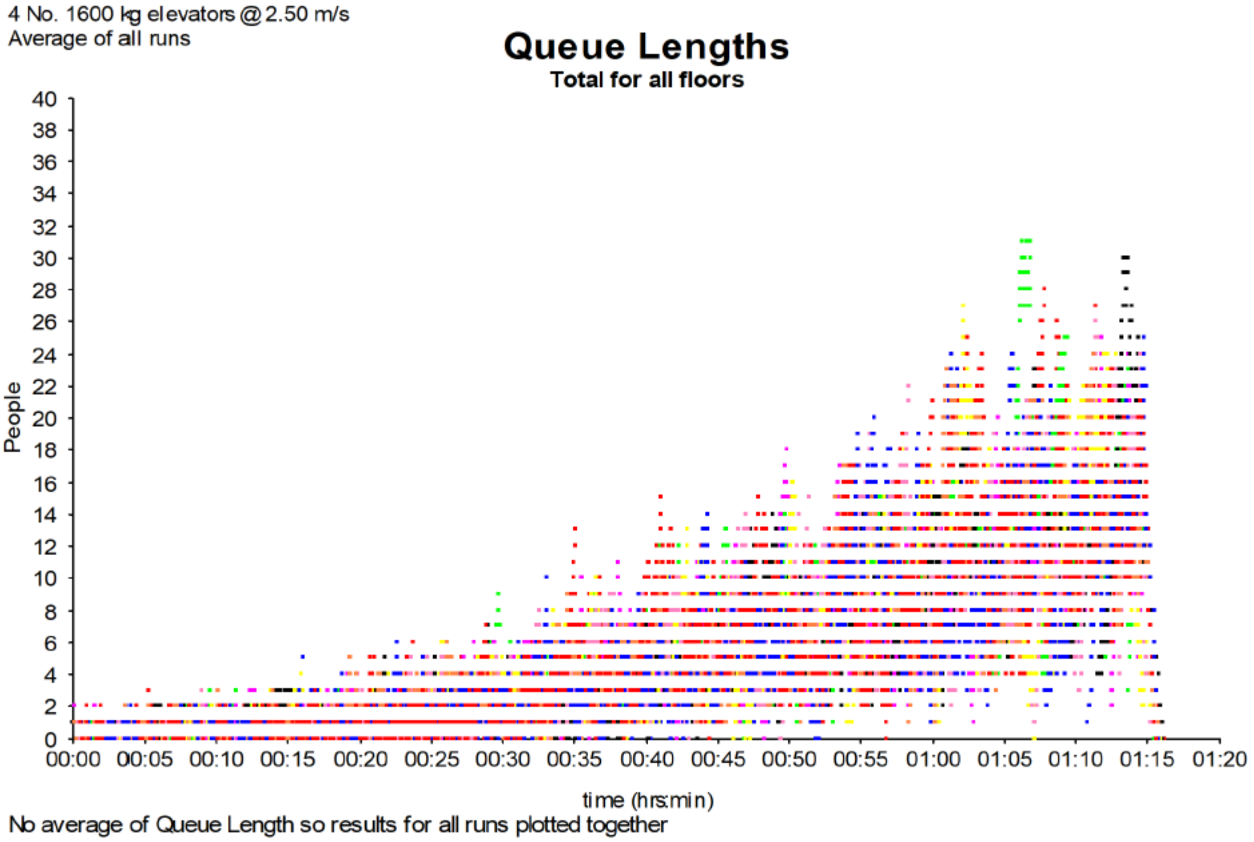
Queue lengths become intolerable at 52 minutes, leaving passengers waiting at the lift lobbies for the next car. 83 persons / 5 Minutes.

Queue Lengths of up to 16 persons.

Average Waiting Time - 23.5 s.

Time to Destination - 65.4 s.

8.2 Estimated Time of Arrival



Graph 2 Elevate step profile for Estimated Time of Arrival control algorithm

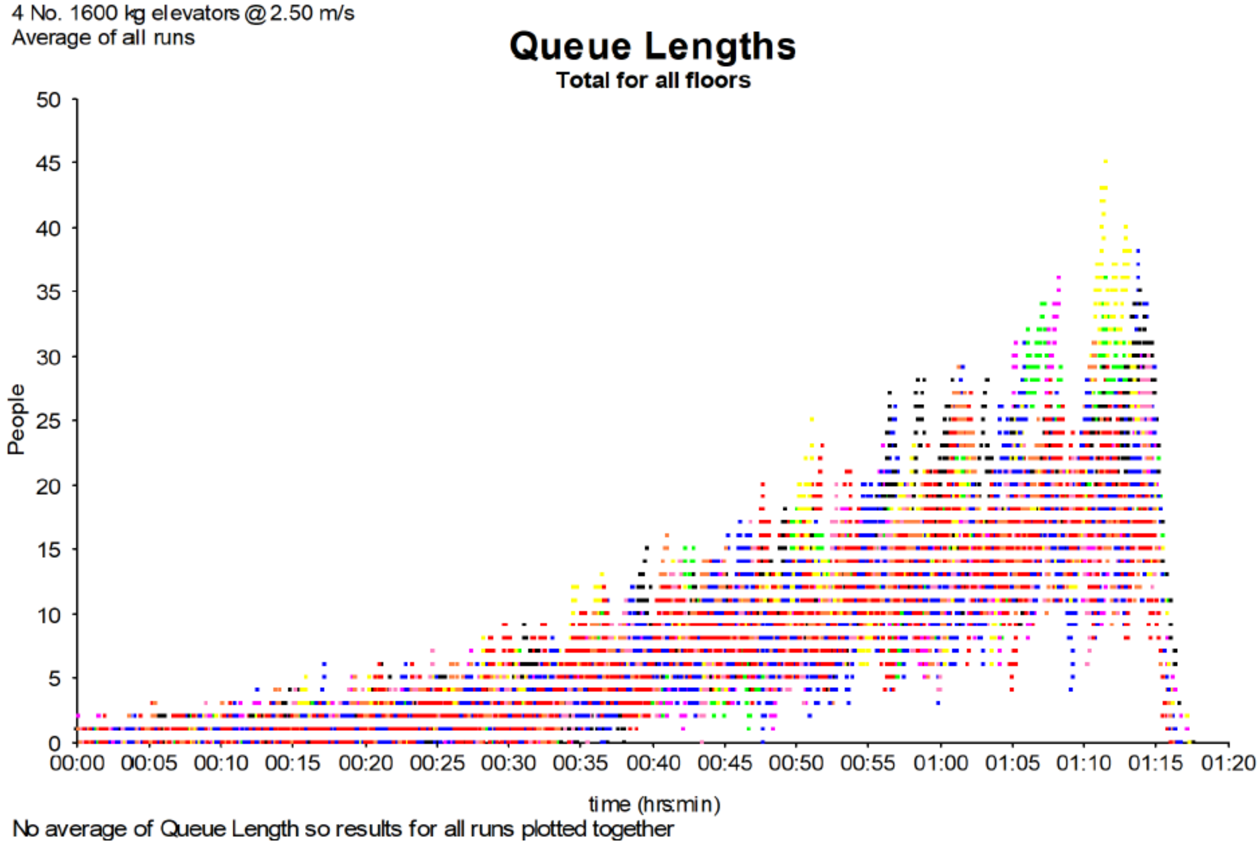
Queues rise and not being cleared at around 55 minutes. 91 person / 5 Minutes.

Queue Lengths of up to 18 persons.

Average Waiting Time - 22.7 s.

Time to Destination - 62.4 s.

8.3 Hall Call Allocation



Graph 3 Elevate step profile for Hall Call Allocation control algorithm

Queues rise and not being cleared at around 38 minutes - 68 person / 5 Minutes.

Queue Lengths of up to 17 persons.

Average Waiting Time - 33.2 s.

Time to Destination - 66.4 s.

Page:	1 of 5
Job:	Unity Square
Job No:	541002
Calculation Title:	Block C - Simulation - Step Profile
Made By:	BKV
Check By:	
File/Date:	Unity Sq-Block C-Peters Lunch (4x1600x2.5)-NCA (404020).elvx 12 Nov 2017 18:55:01

ELEVATE

Elevate Version 8.19 (Build 2206)
Abbacas Consulting Ltd

ANALYSIS DATA

Analysis Type	Simulation
Measurement system	Metric
Dispatcher Algorithm	Group Collective Traffic mode: Normal
Time slice between simulation calculations (s)	0.10
No of time slices between screen updates	10
No of simulations to run for each configuration	10
Random number seed for passenger generator	1
Energy Model	On
Currency	£
Price per kWh	0.12

BUILDING DATA

Floor Name	Floor Height (m)	No of people	Area (m²)	Area/person	Entrance Floor
Basement	3.00	0	-	-	Yes
Lower Ground	3.00	0	-	-	Yes
Podium - Ground	3.50	107	1280.0	12.0	Yes
1	5.50	149	1787.0	12.0	No
2	4.00	160	1921.0	12.0	No
3	4.00	160	1921.0	12.0	No
4	4.00	160	1921.0	12.0	No
5	4.00	90	1083.0	12.0	No
6	4.00	90	1083.0	12.0	No
7		90	1083.0	12.0	No

Absenteeism (%)	10.00

ELEVATOR DATA

No of Elevators	4
Type	Single Deck
Capacity (kg)	1600
Car area (m²)	3.56
Door Pre-opening Time (s)	0.00
Door Open Time (s)	1.50
Door Close Time (s)	2.50
Door Dwell 1 (s)	3.00
Door Dwell 2 (s)	2.00
Speed (m/s)	2.50
Acceleration (m/s²)	1.20
Jerk (m/s³)	1.00
Start Delay (s)	0.50
Levelling Delay (s)	0.00
Home Floor	Podium - Ground

PASSENGER DATA

Arrangement	Conventional for Single Deck elevators
Template	Step profile
Minimum (% pop per 5 mins)	1.00
Maximum (% pop per 5 mins)	15.00
Step duration (mins)	5.00
Step height (%)	1.00
Incoming (%)	40.00
Outgoing (%)	40.00
Interfloor (%)	20.00
Passenger Mass (kg)	75
Passenger Area (m²)	0.21
Loading Time (s)	1.20
Unloading Time (s)	1.20
Stair Factor (%)	5.00
Capacity Factor by Mass (%)	80.00
Capacity Factor by Area (%)	100.00

Floor Name	Entrance Bias
Basement	8.00
Lower Ground	8.50
Podium - Ground	83.50

Figure 4 Example of the Elevate data for the simulations

Except for the Despatcher Algorithm the detail was the same for each Step Profile simulation

9 OBSERVATIONS

The HCA performance saturates quicker than the NCA and ETA.

The ETA performs for a little longer than the NCA.

To check the trend, two further Step Profiles were run:

A larger peak - 70 % up traffic, 20% down traffic and 10% inter-floor.

A more closely balanced traffic mix - 35%, 35%, 30%.

The results of all the Step Profiles clearly indicate all three control systems saturating sooner as the inter-floor mix rises. However, in each case the ETA held out a little longer. Not by a large margin, once again the difference is small and subtle.

Like the original investigation, these results felt counter intuitive, especially considering the claims made by some of the more vocal advocates of Hall Call Allocation.

10 CONCLUSIONS

From these results and observations, it was clear that each control system reacts and responds differently. This is further supported by other academic studies.

Unless enhanced with sectoring or zones. the Next Car Available system can only react to the calls placed on the system; it follows a very simple algorithm.

The ETA has a little more "intelligence"; it responds to differing lobby conditions as it monitors how long a Hall Call has been placed. A Hall Call's priority increases with time and is answered sooner.

The HCA responds to the initial information (i.e. numbers of passengers and which floors they want to travel to). It will consider all permutations before allocating a lift car to a passenger.

On face value, the HCA appears to have most of the advantages. It reduces journey times and makes better use of the cars by grouping people together. It reduces the possibility of duplicate journeys and cars following each other. Waiting Times may be a little longer, but the overall journey time can be reduced as the lift cars make fewer stops. The Round Trip Time (RTT) consumes less time [6].

The HCA control system out performs the traditional NCA and ETA systems in peak conditions. However, it struggles with increased two-way inter-floor traffic found during a lunch peak as there are fewer opportunities to group passengers as effectively as there are in peak conditions [7].

A well-designed HCA will provide improvements over an NCA. However, when the demand changes, a good ETA system will provide a small advantage, due to its ability to constantly re-evaluate the calls as new people arrive and place Hall Calls. The HCA is unable to re-evaluate; its decision is based on the information provided by the passengers as they arrive. Its intention has been announced, the lift car is committed; it is final and irreversible.

So, the answer to the investigation. Simply put, it is all due to the ETA's ability to adapt to change!

As revealed by this enquiry, the results of the calculations and simulations can be subtle and need to be carefully examined and interpreted. Each system considered need be vigorously tested under various traffic profiles to reveal the performance, the benefits and the disadvantages.

Some eager sales personnel are offering Hall Call Allocation as a panacea to all lift problems. In some instances, it works well but as this investigation has revealed there are limitations. It may therefore be appropriate to conclude with an axiom, "Designer be aware"! That is; be aware of all the benefits and the limitations of each system considered.

Whilst being attentive to the latest technologies, designers will serve their clients and the users of the system better when exercising even more care; reviewing all the foreseeable traffic probabilities, and control combinations, before making recommendations or offering solutions.

11 EPILOGUE - HALL CALL ALLOCATION - THE FUTURE?

The quest for a more responsive Group Control System – two possibilities:

Hybrid systems: - As described by Len Halsey [10] where the control system consists of two parts, with the HCA system on the main floor(s) to cope with the uppeaks and a standard two button system on the upper levels to improve the inter-floor traffic performance. From this investigation it appears that the upper floors will be better managed by a well-designed ETA based algorithm.

An internet of things: – Maybe Apple, Google or Microsoft will develop applications that interface with the HCA controller. Then re-evaluation and car changes could be instantly brought to the attention of the passengers via a smart phone, watch, ear buds, necklace, etc.

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BIOGRAPHICAL DETAILS

Barry Vanderhoven started in the industry as a lift and escalator apprentice in the early 70s with Marryat & Scott and has worked in many departments and disciplines within the VT world. Barry has been a Director and joint owner of Abbacas Consulting Ltd since 1995.

Lifting Elevators into the Cloud – Permanent Detection of Wear Using Intelligent Sensors

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Keywords: predictive maintenance, internet of things, cloud, lift monitoring, machine learning algorithms, wear detection

Abstract. Condition Monitoring Systems for elevators going beyond a mere display of stored faults or counter readings are hard to find on the lift market. Yet, only a few sensors already allow the monitoring of significant components of a lift system to ensure that wear is detected at an early stage and appropriate servicing recommendations are automatically generated. As such, a predictive maintenance of lifts is possible, which saves a lot of resources and time and nevertheless warrants a high availability of the lift system. Especially for retrofitting of existing lifts an intelligent device is needed, which doesn't need communication to the lift controller. Within the context of a field trial, several lift systems worldwide have been equipped with an IoT-device (Internet of Things) which evaluates every single elevator ride on the edge using intelligent algorithms permitting the wear of individual component groups to be detected. The collected data, resulting messages and alerts are transmitted automatically via the internet by a standard protocol into a cloud, where extended Big Data Analysis is done.

1 INTRODUCTION

The industrial Internet of Things (IoT) and its Digital Twin surrogate are fuelling exciting conversations about business process innovation on the factory floor and in industrial equipment manufacturing. One hot area in particular is the broad and often loosely-defined practice of Predictive Maintenance (PdM) of complex machinery as lifts are too.

As is frequently the case when technology innovation is trying to penetrate an established business practice, there’s a good dose of hype and optimism on the side of technology pundits, countered by scepticism and resistance to change from maintenance organizations and experienced field service technicians.

Both sides must work together to create a functioning PdM solution. Neither Big Data Analysts, nor lift engineers or field technicians will be able to do this alone. Only when domain knowledge about lifts, metrologic know-how for lifts, and data analysts' knowledge of algorithms and statistics are brought together, can an efficient, economical, and, above all, functional solution succeed, which can then be the basis for a change in business models in the lift industry.

2 STRATEGIES TO ACHIEVE PREDICTIVE MAINTENANCE FOR LIFTS

2.1 Make the lift controller an IoT device does not provide PdM

Throughout the industry, but especially in the lift market, the controllers of the machines are connected to a cloud via the Internet under the slogan Predictive Maintenance. Technically, this is not far away from the remote data transmission for lift control systems, which was practised more than 20 years ago. And this method actually only allows a Preventive Maintenance. Preventive Maintenance of lift systems is carried out on the basis of intervals: within fixed intervals or after reaching a certain number of rides, door movements etc. Finally, the connection of the lift control to a cloud no longer provides information about the lift, as they would be available to the technician on site. Of course, access, management, linking to support documents and the like is much more comfortable than it used to be, *but this is not a Predictive Maintenance solution*.

2.2 Use of Sensors for Condition Monitoring

Today and in nearly all industrial areas Condition Monitoring is one of the mainstays needed to efficiently operate and service technical plants. This concept is based on a regular or permanent recording of the condition of the machine by measuring and analysing meaningful physical parameters. The technological developments achieved in sensor technology, tribology and microprocessor technology allow an unparalleled quantity and quality of information to be used for the maintenance of lifts too. An industrial environment cannot be pictured without Condition Monitoring any more. It must more or less be regarded as a compelling requirement for a condition-oriented predictive maintenance. The more comprehensive the maintenance strategy and the requirements it has to meet, the more distinctive will be the significance of Condition Monitoring.

The real challenge lies not in the selection of the sensors (this is where the domain knowledge of lift experts is necessary, but also available), but in the evaluation or processing of the sensor data.

2.2.1 Getting advantages from the collected data

Usually IoT vendor presentations suggest that further examination of misunderstandings and perhaps exaggerated expectations from PdM technology is in order.

One model to rule them all. The implied assumption that similar devices generate identical sensor data patterns and therefore a machine learning algorithm can handle multiple devices in the installed base is flawed. In reality, no two mechanical systems are alike even as they roll off the production line. And they begin changing as soon as they are put into duty. The baseline data generated by rotating and reciprocating equipment is highly configuration and application specific, and changes continually throughout the life of the asset due to wear and tear, different duty cycles, and operation and maintenance practices. Machine learning algorithms must adapt to these changes without compromising detection precision or suffering from an increasing rate of false positives.

The Digital Twin provides the ability to track and analyze each asset individually, allowing the machine learning apply context beyond machine-generated sensor data, such as configuration and maintenance history. Although the digital twin is essential to implementing a PdM system, the focus on individual as-maintained unit configurations also highlights a potential concern: if, over time, assets drift to the degree they are no longer similar, the ability to conduct any type of broad installed base analysis is impeded. [1]

Machines learning algorithms do all the work. Machine learning enthusiasts seem to propose something little short of magic. Just feed the software with a wealth of machine-generated data, and AI-based algorithms do all the work on their own. They remove signal noise and data outliers, and smooth data just enough so no key features are lost; they identify the best-suited analytic algorithm; and provide highly accurate data trending and failure prediction. The reality can prove to be more complex, to say the least. Early adopters find that while building a proof-of-concept model is a manageable effort and the results can be very impressive indeed, these initial models can be difficult to scale, as the models must be validated for a much broader range of product configurations and applications, and be able to adopt to changes induced by cyclical changes and wear and tear. The effort to test and validate machine learning algorithms cannot be underestimated. Some types of artificial intelligence systems require regression testing every time a change is made. Ohers, black box type systems, such as neural networks, cannot be trusted blindly based on test results from limited training data. [1.2]

3 REQUIREMENTS FOR A PREDICTIVE MAINTENANCE SOLUTION FOR LIFTS

As is apparent from what is previously mentioned, it is not sufficient to equip a lift system with the highest possible number of sensors and send the measurement data via an Internet connection to a cloud, which would then send back the following maintenance recommendations, wear reports, and others to the appropriate locations. In addition, there are other boundary conditions, which will be briefly touched on here.

3.1 Independence from the lift control

A PdM lift solution must be completely independent of the controller. The diversity and also the small number of open protocols in lift construction would otherwise not permit the widespread application of the system, since the portfolio of every lift service company always includes systems from third-party manufacturers.

3.2 Cost efficiency

It is obvious that a PdM solution is only advantageous if it also saves costs and this not only during operation, but during the entire period of use including the installation of the PdM device. With very few installations, it can be assumed that a PdM solution was already provided for the construction of the system, so special value should be placed on efficient retrofitting.

3.2.1 Efficient installation

An efficient installation requires that the number of sensors used is manageable and easy to install. An installation time of a maximum of two hours should not be exceeded. This assumes that the device remains independent of existing components of the lift and no taps are made of the existing electrical and electronics, which would also require further documentation in schematics, etc. Also, the intended data transfer to the cloud must be chosen wisely, so as not to interfere during installation, e.g. the hanging cable must be extended by data lines to allow an antenna in the shaft head.

3.2.2 Selection of the sensors

Of course, the number of sensors should be as limited as possible, yet still monitor as many crucial components of the lift as possible. Of course, for each sensor, the costs and benefits must also weighed. A very interesting approach is the use of virtual sensors, which generate new measured values from the data of other physically existing sensors without the sensor actually having to exist.

3.2.3 Distributed intelligence

If the know-how for this is available, it makes sense to apply as much computing power as possible already in the PdM device on the lift system. This greatly reduces the effort of data transfer and can offer significant benefits depending on the choice of analysis concept. These preprocessed, on-the-edge generated data can then be transferred to the cloud, making it available for subsequent Big Data Analysis.

3.2.4 Data Transfer

Data transfer can only be cost-effective if no sensor raw data is transmitted. Instead, already aggregated data or only results should be transferred. Depending on the state of development of the PdM systems, today it is possible to find systems in the lift industry that transmit more than 20 gigabytes per month, but also smart systems that manage with only a few megabytes per month. In addition, the system should not rely on the assumption of a constantly available Internet connection - especially in lift systems this can only be achieved with great financial expense.

4 IMPLEMENTATION OF A PREDICTIVE MAINTENANCE SOLUTION FOR LIFTS

The above requirements have been implemented in a PdM system based on only two physical sensors: A 3-axis accelerometer mounted on the cab support frame and a load sensor that detects the current load in the car. A single-board computer continuously samples this raw data and recognizes in real-time (without any connection to the lift control system) the current driving condition of the lift system and the current position of the car in the shaft. From the two physical sensors, several hundreds of virtual sensors are calculated, which relate to specific components of the lift installation, such as e.g. traction sheave, frequency converter, door guides, door drives, etc. refer.

These data are generated at the unit itself and are statistically condensed. Actually, every lift trip is included in the calculations and thus generates a chronological progression over the virtual sensors over the individual days, weeks and months. The number of actual virtual sensors of several dimensions, and others, depending on the number of stops. For a system with 10 stops, there are a total of over 8,000 virtual sensors. Their progressions are monitored by the one-board computer for significant changes, so still on site at the lift system. If certain conditions are met, alerts are generated and sent to users via the cloud. In addition to the affected component, such warnings may also include the position in the shaft or the floor concerned and a corresponding action recommendation.

The algorithms for detecting wear and component problems are chosen so that user intervention is not necessary, since the monitoring and parameterisation of just under 800 limit values per stop by a user is hardly feasible and certainly not cost-effective to implement.

The compressed data from the virtual sensors is also transmitted to the cloud where it is further analysed in Big Data Scenarios to generate more in-depth inferences and recommendations based on the data of all monitored lifts and to find new relationships with the help of neural networks. This concept allows a lift system with, for example, 10 stops with less than 3 megabyte payload data per month to be operated on the cloud.

In addition to Predictive Maintenance, such a system can also be used for traffic analyses, as all stops, payloads and door movements approached are detected autonomously. Furthermore, derived functions such as person inclusion (no door movements after the end of the journey and payload greater than zero), emergency stops, etc. implemented and can be used as sources of information for emergency calls and error messages.

5 SUMMARY

Lift Predictive Maintenance requires sensor-based Condition Monitoring. Although numerous solutions already advertised on the market use the keyword PdM, they turn out to be the decades-old Preventive Maintenance approach, which now uses modern technologies such as IoT and Clouds, but ultimately only provides lift control data to the user.

Conclusive concepts, which were also implemented in real existing devices, are only occasionally found on the market and sometimes the look behind the scenes of these systems is very disappointing. Nevertheless, lift operators worldwide are beginning to demand service contracts based solely on availability and lift companies are beginning to offer them. Medium-sized service companies are only beginning to realize what changes will be made to the lift industry and make changes to their business model necessary.

In any case, this kind of cost-intensive preventive maintenance strategy for lift systems will soon be a part of the past. The only adequate countermeasure which will be able to compensate the partially massive cost reductions affecting lift components in the past few years can only be in form of an automatic wear and tear monitoring of safety-relevant and function-critical components.

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BIOGRAPHICAL DETAILS

Tim Ebeling has been employed since 2003 as head of development with Henning GmbH & Co. KG. In this capacity he has established the R&D centre in Braunschweig (Germany). A team of employees is now working there on the development and production of electronic and measurement components for lifts. Since 2012, the author is also managing director and since 2015 also a shareholder of the company. One of his particular focal points is the measurement technology. Especially in this area the author looks back on many years of experience in the development of acceleration and rope load measuring systems. The author's professional goal is to enrich the lift market with innovative lift components and opposing the increased cost pressure in the lift industry through the development of efficient sustainable and labour-saving components.

New Ways to Approach EMC in Lift Industry. Case of ITER[1] Project

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Keywords: lifts, ITER, innovative, magnetic field, electromagnetic compatibility, testing, environmental responsibility

Abstract. Over the years, designs have been developed considering the requirements of Electromagnetic Compatibility (EMC) for lifts, following the EN 12015 & EN 12016 standards, to achieve and increase quality and reliability. To achieve this, EMC requirements are considered from the first steps of the design, other requirements are established when testing in a laboratory and, then, collaborations have been carried out with partners to achieve the EMC compliance of the complete electrical installation.

A new challenge in EMC currently being worked on is designing lifts for a singular installation: the ITER project. This facility requires special actions to meet such unique requirements as the project is, especially in terms of magnetic fields. The project involves not only a challenge for designing, but also for the companies who cooperate in tests and simulations as they must manufacture ad hoc instrumentation, thus innovating in the process to perform the tests.

1 INTRODUCTION

1.1 EMC requirements

All electric devices or installations influence each other when they are interconnected or close to each other. The purpose of electromagnetic compatibility (EMC) is to keep all those side effects under reasonable control.

Electrical and electronics equipment shall be designed and manufactured to meet the essential requirements of 2014/30/EU Electromagnetic Compatibility (EMC) directive:

"(a) The electromagnetic disturbance generated does not exceed the level above which radio and telecommunications equipment or other equipment cannot operate as intended;

(b) It has a level of immunity to the electromagnetic disturbance to be expected in its intended use which allows it to operate without unacceptable degradation of its intended use."

The Electromagnetic Compatibility (EMC) Directive 2014/30/EU requires that electrical and electronic equipment does not generate, or is not affected by, electromagnetic disturbance. Following harmonized standards, we can get the presumption of conformity with those essential requirements.

1.2 EMC lifts requirements

The Directive 2014/33/EU on lifts indirectly includes EMC requirements: EN 12016 and EN 81-20 standards provide presumption of conformity with the Directive. EN 12016 and EN 12015 are also included in EN 81-20 standard, where the procedure that must be followed by the installer of a lift or by the manufacturer of a safety component, before it is placed on the market, in order to ensure that his lift or safety component complies the Directive. The Lifts Directive details the essential requirements the product must meet to allow the lift installer or the manufacturer of the safety components for lifts can affix the CE marking. The electrical installation of the lift shall comply with the electromagnetic compatibility requirements according to clause 5.10.1.1.3 of the EN 81-20:2014,

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[1] ITER: International Thermonuclear Experimental Reactor

where it is stated that the electromagnetic compatibility shall comply with the requirements of EN 12015 and EN 12016 standards (harmonized standard with the EMC directive). Safety circuit equipment shall comply with special immunity requirements of the EN 12016 standard.

2 EMC REQUIREMENTS FOR LIFTS, EN 12015 & EN 12016

2.1 Emissions requirements, EN 12015

There are two kinds of emission requirements as per EN 12015 standard, conducted and radiated, in three range of frequencies, harmonics limits for lower range (from 2^{nd} to 40^{th} current harmonic, thus up to 2 kHz), conducted limits above 150 kHz up to 30 MHz and radiated from 30 MHz to 1 GHz. Those radiated measurements should be done in a semi-anechoic chamber. Note there are no requirements from 2 kHz to 150 kHz.

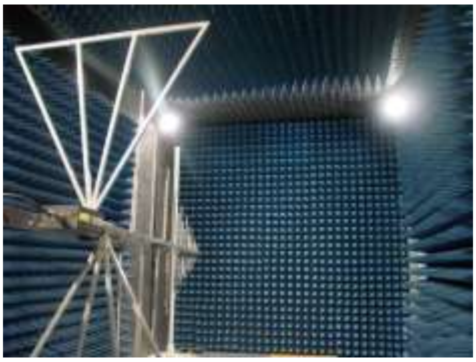

Figure 1 Semi-anechoic chamber in the EMC laboratory. Courtesy of MP Lifts

2.2 Immunity requirements, EN 12016

This European Standard specifies the immunity performance criteria and test levels for apparatus used in lifts, escalators and moving walks which are intended to be permanently installed in buildings including the basic safety requirements in regard to their electromagnetic environment.

The standard refers to EM conditions as those existing in residential, office and industrial buildings. This standard addresses commonly known EMC related hazards and hazardous situations relevant to lifts when they are used as intended and under the conditions foreseen by the lift installer or manufacturer.

However, performance criteria and test levels for lifts do not cover situations with an extremely low probability of occurrence. It does not include magnetic field immunity tests that are applied to other products, such as information technology equipment, according to EN 55024 standard.

2.3 Collaborations

The compliance of EMC requirements is not only a matter of affixing a CE marking to the product and signing the EU declaration of Conformity. It has also to do with achieving and increasing the quality and reliability. To do so, the EMC requirements are considered from the first steps of the design, other requirements are established when testing in a laboratory and, then, collaborations are carried out with partners and providers to reach the EMC compliance of the complete electrical installation. We usually collaborate with Universities, technological centres and independent experts during the design process.

It is necessary to define internal protocols to go further than those indicated in the standards, thus ensuring the robustness of the product design. Immunity tests applied with safety factors between 2 and 8, and acceptance criteria more stringent than those specified in the standard, may reduce fails and damage in lift electronics.

3 CASE OF ITER PROJECT. SPECIAL EMC REQUIREMENTS

The International Thermonuclear Experimental Reactor (ITER) is a project to prove that fusion power can be produced on a commercial scale and it is sustainable. The Tokamak is an experimental machine designed to harness the energy of fusion. ITER will be the world's largest Tokamak machine, with a plasma radius (R) of 6.2 m and a plasma volume of 840 m³. Fusion is the process that powers the sun and the stars: when light atomic nuclei fuse together to form heavier ones, a large amount of energy is released. Fusion research is aimed at developing a clean, safe, abundant, economic and environmentally responsible energy source.

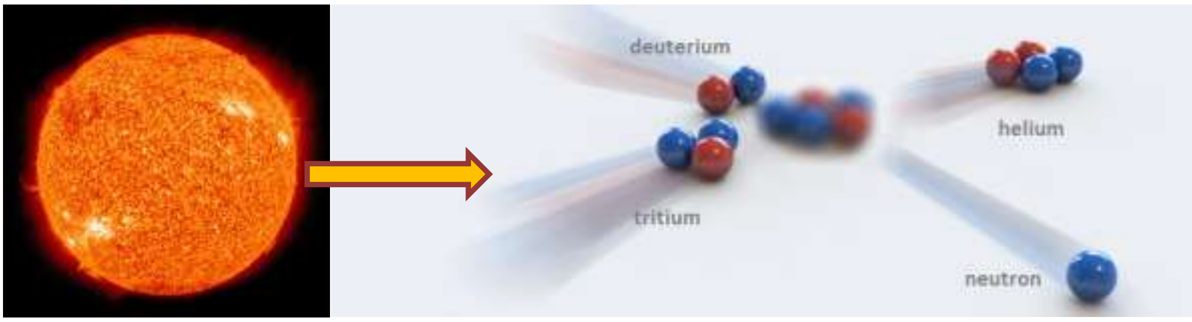

Figure 2 Fusion process in the sun

The ITER facility is being built in southern France by a scientific partnership of 35 countries.

Six ring-shaped poloidal field magnets will surround the toroidal field magnet system to shape the plasma and contribute to its stability by "pinching" it away from the walls. The largest coil has a diameter of 24 meters; the heaviest is 400 metric tons.

This means that all the equipment inside the reactor buildings will be subjected to high DC magnetic fields included the lifts. Also, electromagnetic interference could affect the stability of the plasma.

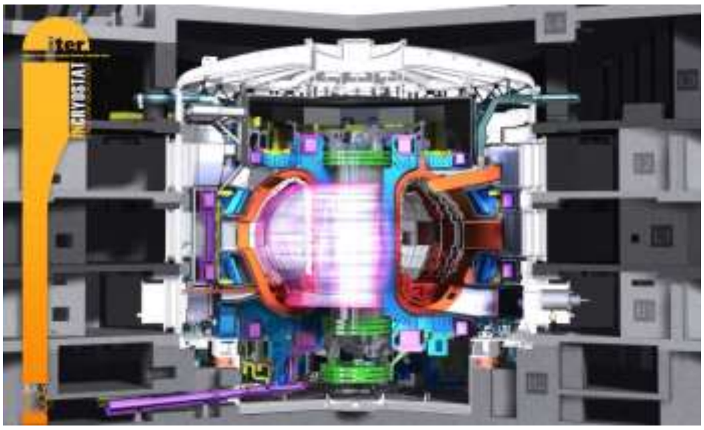

Figure 3 Tokamak machine diagram

When the author arrived at this project, as the responsible technician for electromagnetic & radiation design of the lifts, it was definitely the biggest technological challenge in his professional career. He was in charge of carrying out all the studies and tests related to electromagnetic field and radiation to ensure the viability of the lifts in the environment of the ITER project.

4 TECHNOLOGICAL CHALLENGES

In the ITER project, a series of extremely tight requirements must be considered where the EMC ones are especially important. As a matter of fact, the electromagnetic disturbances of the building equipment could affect the stability of the reactor plasma. If that happens, it would have catastrophic consequences.

For the lifts, we considered the here below EMC requirements in the qualification process:

- Emission limits according to EN 12015 standard.
- Specific conducted emission limits, tested according to MIL-STD-461F (CE 101/2).
- Immunity according to EN 12016 standard.
- Immunity to fluctuating magnetic fields (50Hz). It was tested according to EN 61000-4-8, with specific levels.
- Immunity to DC magnetic field requirements with specific field level up to 20mT. It was tested according to EN 61000-4-8 and a specific methodology (defined in clause 5.4).

There are two key aspects of the requirements to be met that represent a technological and new challenge for lifts to achieve the goals:

- Specific conducted emission limits, tested according to MIL-STD-461F (CE 101/2), from 50 Hz up to 30 MHz, covering a new range of frequencies for lifts: from 2 kHz to 150 kHz, and stricter limits for frequencies upper than 150 kHz. Thankfully, the goal was reached and we only had to apply traditional EMC resources, like a few decoupling capacitors.

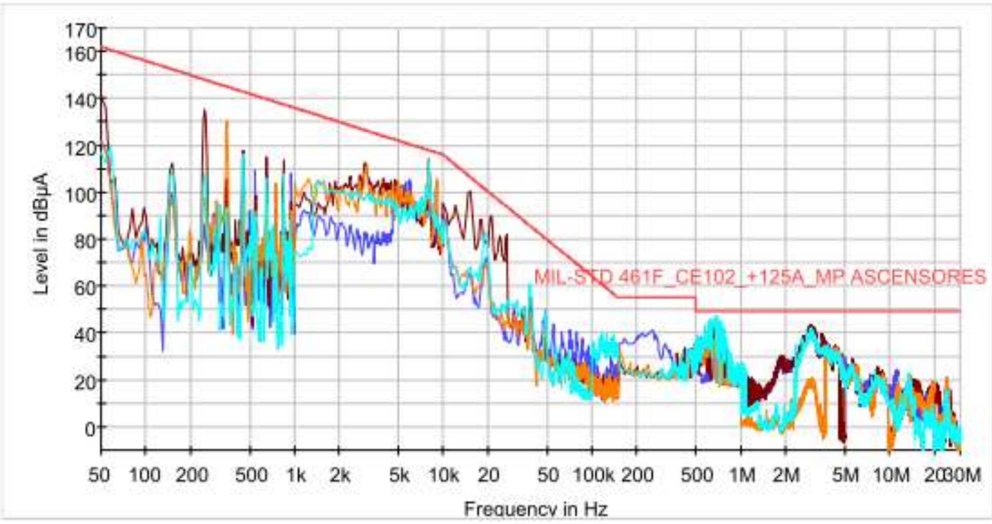

Figure 4 Conducted emissions results according to MIL-STD-461F for goods lifts.

- However, the bigger challenge was the immunity to magnetic field due to the following reasons:
  - The company never had any experience in this kind of test, only with communications devices in the car (emergency phone), with much lower levels.
  - Non-existent instrumentation for specific requirements, because the level of magnetic field had never been never tested before. It was a challenge for us and for the laboratory. EN 61000-4-8 standard levels are in the range of µT, and DC magnetic field level are 20 mT (thousands times greater).
  - These issues generated high uncertainties.

    - Both electric and mechanical components had to be considered due to the effects that could be produced by magnetic field: movement, heating, etc.

Hereafter, we will only deal with the magnetic field requirement that it is the greater innovation brought and tested.

5 MAGNETIC FIELD ACTIONS: ANALYSIS, SIMULATIONS & TESTS

To achieve the compliance with the requirements of magnetic field, a path of actions had been set, considering three steps: analysis, simulations and tests.

5.1 Analysis

An analysis phase was developed, where the following actions were carried out:

- A documentary and detailed review of the requirements; as we will see in next chapter.
- A design review of the electric installation to locate critical components based on its operating principle (for example: magnetic positioning) that could be affected by the field.
- Meetings with the responsible technicians for electromagnetic compatibility laboratories where magnetic field immunity tests are usually carried out.
- Meetings with the manager of the nuclear fusion laboratory in Madrid, to know the effects and mitigation measures applied to solve the problems in their instrumentation.
- Support of external consultants: University of Seville and Technological Institute of Aragon.

And, of course, we always had to apply a large amount of common sense.

The result was that we were lead to some inevitable design changes and new resources for the protection of critical equipment were required. But we also got the base of experience that was not available at the beginning and the conviction that nobody had been faced to a similar problem before.

5.2 Requirement analysis

As already mentioned, it was performed a comprehensive analysis of the necessary requirements, to know exactly which lift components had to be tested, which resources have to be dedicated to, which were the protection options, which kind of resources can be used to apply solutions and measurements during the tests.

The analysis conclusion was that the test would be passed if the lift operation remained correct in presence of the magnetic field, considering these additional points:

- Functional point of view:
    - log of car and landing calls,
    - car motion to all the floors from where a call is made,
    - information on the car display,
    - emergency mode and communications,
- The magnetic forces do not generate any missile effect (capability of the static magnetic field to attract ferromagnetic objects, drawing it quickly by considerable force).
- No fire breaks out due to overheating or currents produced by the magnetic field.

If the magnetic field has a residual effect on ferromagnetic parts of the lift, it can generate heavy soiling with effects in the mechanical functions. This point has to be considered for the maintenance works. We also need to evaluate that the entire electronics works properly (not only functionally).

5.3 Simulations

Simulations of the magnetic field to critical facilities for the ITER in reactor buildings were performed in order to evaluate possible solutions to the magnetic field issues.

These studies were developed in collaboration with ITAINNOVA ("*Instituto Tecnológico de Aragón*"), which is a technological centre, and whose specialists were our advisors.

The first step consisted of looking for protection options through the simulations: full protection of the lift shaft vs individualized protection only for critical parts.

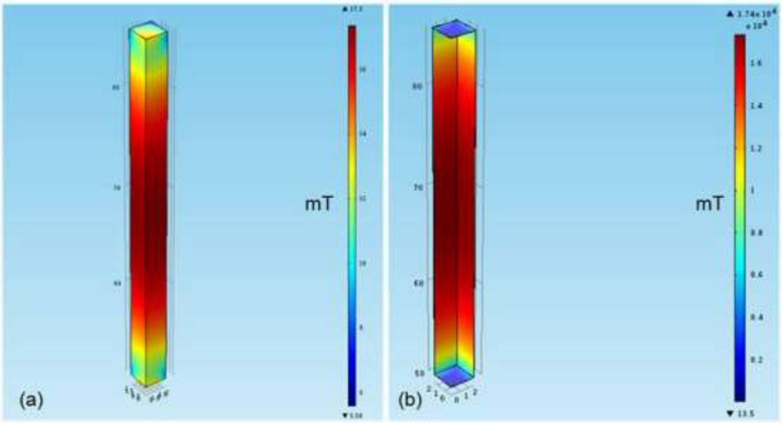

Figure 5 Shaft simulation. Magnetic field inside the shaft with complete shielding.

The first result ruled out the complete protection. So we started to simulate individualized shielding for critical parts of the lifts: control box, landing operating panels, car operating panels and harmonic filter protections.

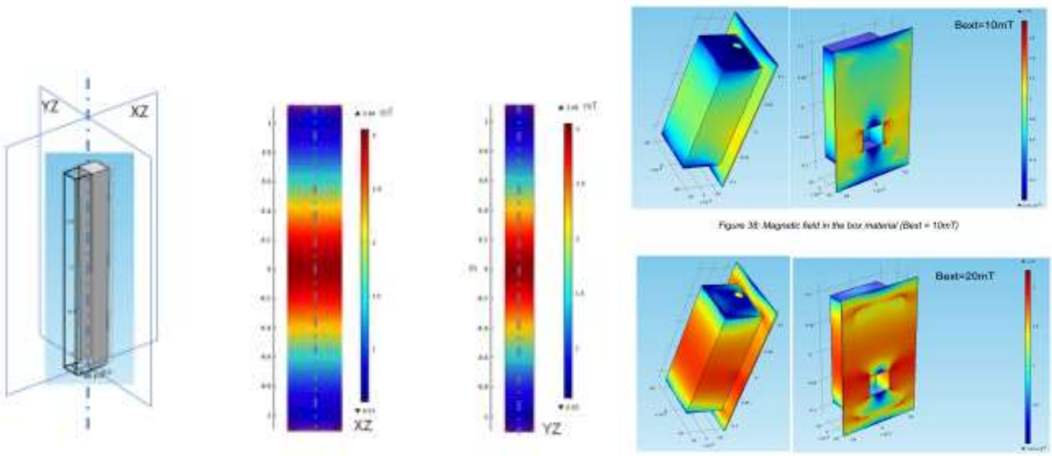

Figure 6 Simulation of the magnetic field inside the protected control box and landing operating panels.

This step result was that we found out how to get prepared for the testing phase, and we selected all the protection alternatives, materials, thickness, shape and designs.

5.4 Tests methodology

The laboratory selected to verify magnetic field requirements was the Official Central Electrical Engineering Laboratory (LCOE). This technical body is accredited by ENAC, according to ISO/IEC 17025. It is also Notified Body for EMC Directive (2014/30/EU). In that laboratory, we tested the following requirements:

a) Immunity to fluctuating magnetic field (50 Hz): EN 61000-4-8 standard.

b) Immunity to static magnetic field (DC): with levels up to 20 mT.

As there was not any international standard related to this subject (DC field), we designed the test methodology to certify the lift operation for the existing magnetic field in the buildings.

For this test, an antenna, provided with a special coil and able to support the current to achieve the required DC magnetic field, had been purpose-built. Other laboratories were also contacted, but they did not have power supply enough to apply this level of magnetic field. This fact gave to us an idea about how difficult it is to test and to accomplish the requirement.

The DC magnetic field range in the buildings is between 1 mT to 10 mT at the levels and rooms where the lifts are. And, according ITER requirements (2X safety factor), the level of 20 mT is selected for testing personnel lifts and 10mT for goods lifts.

The assembly of apparatus had to pass the functional performance criteria in such a way it had to continue to operate as intended. No degradation of performance or loss of function is allowed below a performance level, when the assembly of apparatus is used as intended.

As per the specific requirements, it has to be ensured there is no generation of any missile effect, nor fire (caused by overheating) due to the magnetic forces and currents produced by the Tokamak magnetic field.

From the analysis of the requirements, the first conclusion was that several measurements had to be applied. A new test methodology (see Table 1) was developed, whereby a series of additional measurements during the magnetic field application tests were done to detect other non-visual effects:

- The performance of functions of the lift was observed by visual inspection of the correct operations and means of the own resources (informative tools of the control electronics) of the electrical installation: informative LEDs, console and car display. This is the traditional method for general requirements: visual monitoring of the sample.

- Input current measurements were made in the power supply of the installation, and this measure can give us a qualitative idea how EMC filters and electronics works, to evaluate it. If the current measurements are modified, there are indications that the electrical installation is working with different conditions (For example, if the harmonics filter fails, then current measurement increase its value when the nominal speed is attained).

- Thermographic measurements were made at the start and end of each test. This one can clarify if any current is produced by the magnetic field in some mechanical parts.

- Residual magnetism measurements were made on the components under test by a gaussmeter.

Type	Requirement	Effect	Measure
General	Functional performance criteria	Failed operations due to magnetic field	Visual monitoring
Specific (ITER)	Not missile effect	Moving parts	Visual monitoring
	Not fire	Overheating due to the magnetic forces and currents in metallic parts	Thermographic measures
Specific (MP)	Residual magnetism	Heavy soiling in mechanical parts	Gaussmeter measures
	Filters and electronics	Operation of electronics and filters	Current measures

Table 1 Methodology summary

5.5 Tests results

The tests in the LCOE laboratory started in October 2017 and ended in April 2018. Tests were carried out on samples of the passenger lift, and the goods lift.

During the tests, some effects were found on the residual current circuit breaker, the contactors and the door operator. All those effects were resolved by using the shielding designed during the simulation phase, changing some metallic parts to stainless steel and changing magnetic sensors by mechanical contacts.

To check if magnetic field had a residual effect on the components (magnetic remanence), magnetic field measurements were performed with a gaussmeter on critical components after the tests. With this measure, we identified the critical components to be verified during the maintenance works.

With a thermographic camera and multimeters, the author had been able to state that there are no thermal and current effects and, also, the electronics and filter operations are right.

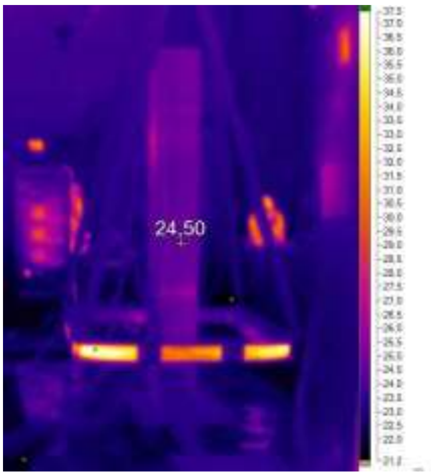

Figure 8 Thermographic picture. MRL control panel.

Figure 7 MRL Control panel

6 CONCLUSIONS

Thanks to the detailed analysis of the environmental requirements at ITER buildings, the simulation phase, the application of additional measures during the monitoring of the tests and the construction of new instrumentation resources to generate the required field, the qualification of the samples has been obtained successfully.

To meet this result, a global view (mechanical, electrical and electronic) of the samples under test has been applied.

Finally, our lifts move upward the raw material to get the clean energy of the future and the people involved in the project. And, in the other hand, these people go on moving further and higher. We will be there to come along with them.

ACKNOWLEDGEMENTS

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LCOE Team: Javier Sánchez, Eduardo Lorenzo, José Vicente García.

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BIOGRAPHICAL DETAILS

José Carlos Feria Moreno is B.Sc. degree in electrical engineering (University of Seville) and works in the R&D department at MACPUAR SA since 1998. He started working in the laboratory of EMC: testing and providing EMC solutions to MACPUAR SA products. Since 2009, he is currently responsible for Electronics and Electrical R&D laboratories where functional, thermal, electronic characterization, electromagnetic compatibility and other tests are being run. He has an extensive experience in EMC, testing resources and he had been collaborating in some research projects with the University of Seville.

About ITER Project: As the responsible for Electromagnetic & radiation design, he was in charge of carrying out all the studies and tests related to electromagnetic field and radiation to ensure the viability of the lifts in the environment of ITER project.

Report on Seismic Damages of Lifts and Escalators by Large Earthquakes in Japan

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Keywords: earthquake damage, the great east earthquake, seismic design guideline

Abstract. The devastating earthquake of Mw9.0, so-called the Great East Japan Earthquake, hit the Tohoku district, north east part of Japan on March 11, 2011. About 16,000 people died and 2,500 people were missing by the strong motion and tsunami, and the economic damage was estimated about 16.9 trillion yen in addition to the influence by the nuclear accident of Fukushima Daiichi Nuclear Power Plant. In addition to the main shock, many strong aftershocks occurred in the long term. After that, a strong near-field earthquake called Kumamoto Earthquake occurred in 2016 in Kyushu district of Japan.

The buildings, houses and industrial facilities were damaged in these earthquakes, and various kinds of mechanical equipment set in these structures were also damaged. The Japan Society of Mechanical Engineers (JSME) has set up an investigation committee which has investigated the seismic damage of mechanical equipment in these industrial facilities, for the purpose to understand the situation and cause of the damages in such facilities to contribute to improvement of preparedness for the forthcoming earthquake.

Additionally, investigation regarding lifts and escalators was mainly carried out by the Japan Elevator Association. This paper provides a summary of the investigation regarding the lifts and escalators to contribute to improving the seismic design for forthcoming destructive earthquakes. Typical damage of the lifts and escalators utilized in buildings are also shown in this paper. Although many of the buildings were hit by unexpected massive earthquakes, the damage of the lifts and escalators designed according to the newly Seismic Design Guideline issued in 2009 seems to have been reduced a certain level.

1 INTRODUCTION

Approximately 20% of earthquakes having a Magnitude of 6 in the whole earth occur in Japan and its surroundings, although the area is only 0.1% of the whole earth [1]. This is because Japan is located on the west side of the circum-Pacific seismic zone, and on 4 plates. The oldest record of the earthquake in Japan is year 416 AD.

The first electric passenger lift in Japan was installed in a building in Tokyo in 1890 [2]. However, the building collapsed due to a large earthquake in 1923. After that, lifts in Japan have experienced various large earthquakes, and the Seismic Design Guideline in Japan was revised according to the damage from earthquakes. In this decade, two large earthquakes attacked Japan. One is the Great East Japan Earthquake in 2011, which was the largest earthquake ever observed in Japan. The earthquake had large energy, long duration time and many aftershocks. The other was the Kumamoto Earthquake in 2016 that occurred in the Kyushu Region. In the series of Kumamoto Earthquakes, two large earthquakes had Japan Meteorological Agency (JMA) seismic intensity 7, which is the highest level of the scale to have occurred in Japan.

This paper provides changes of the Seismic Design Guideline in Japan and analyzes damage of lifts and escalators from the Great East Japan Earthquake in 2011 and the Kumamoto Earthquake in 2016.

2 CHANGES OF SEISMIC DESIGN GUIDELINE IN JAPAN

Table 1 shows a history of major earthquake and seismic standards or guidelines.

Before 1971, no official seismic design guideline was established in Japan, so seismic design guidelines established by each company were applied.

In 1972, the Disaster Prevention Standard was established by the Japan Elevator Association. This establishment is based on the damage of lifts by the San Fernando Earthquake in 1971. In the earthquake, a counterweight fell and collided with a car. Thus, the standard considered derailment of cars and counterweights, prevention of overturning of traction machines and control systems, seismic emergency operation and so on.

In 1981, a Seismic Design Guideline was established by the Building Center of Japan based on the damage of lifts from the Miyagi Earthquake in 1978. In the earthquake, derailment of counterweights, movement of traction machines etc. occurred. In addition, Enforcement Ordinance of Construction Standard Law in Japan was revised in 1981, so the Seismic Design Guideline reflected it. The Seismic Design Guideline considered improvement of countermeasures against derailment of cars and counterweights, improvement of prevention of overturning of traction machines and control systems, improvement of countermeasures against entanglements of ropes and so on.

In 1998, a Seismic Design Guideline was issued by the Building Center of Japan based on the damage of lifts and escalators from Kobe Earthquake in 1995. In the earthquake, counterweights fell, and equipment in machine rooms moved and overturned. In addition, damage of escalators was also reported. Therefore, the new Seismic Design Guideline considered addition of countermeasures against falling of counterweight blocks, the increase of design earthquake level and so on. In addition, the seismic design of escalators was newly described in the guideline.

In 2009, the Seismic Design Guideline was revised based on the damage of lifts from the Mid Niigata Prefecture Earthquake in 2004 and the Northwestern Chiba Earthquake in 2005. In the Mid Niigata Prefecture Earthquake, long period seismic waves that had predominant periods of more than a few seconds were generated in Tokyo, so high-rise buildings and wire ropes of lifts resonated. In the Northwestern Chiba Earthquake, many lifts were stopped for a long time by the earthquake emergency operation, and passengers were trapped in lifts, although this earthquake was smaller than other destructive earthquakes. Thus, the revised guideline considered countermeasures against resonance of long ropes, improvement of earthquake emergency operation and so on.

In 2014 and 2016, the Seismic Design Guideline was revised based on the damage of lifts and escalators from Great East Japan Earthquake in 2011 [3]. Lifts and escalators damaged by the earthquake as describe hereinafter, because the earthquake was the largest earthquake ever observed in Japan. In addition, 4 escalators in shopping malls fell from floors of buildings. Thus, the revised guideline considered countermeasures of the falling of escalators, assessment of major support parts of lifts and so on.

Table 1 History of major earthquake and seismic standard or guideline in Japan

Year	Earthquake	Standard / Guideline
1971	San Fernando Earthquake	
1972		Disaster Prevention Standard
1978	Miyagi Earthquake	
1981		Seismic Design Guideline (1981)
1995	Kobe Earthquake	
1998		Seismic Design Guideline (1998)
2004	Mid Niigata Prefecture Earthquake	
2005	Northwestern Chiba Earthquake	
2009		Seismic Design Guideline (2009)
2011	Great East Japan Earthquake	
2014		Seismic Design Guideline (2014)
2016	Kumamoto Earthquake	Seismic Design Guideline (2016)

3 DAMAGE FROM GREAT EAST JAPAN EARTHQUAKE IN 2011

3.1 Summary of earthquake

The Great East Japan Earthquake is a series of disasters that originated in the off Pacific coast Tohoku Earthquake on March 11, 2011 at 14:46 JST. The hypocenter of the earthquake was at approximately 130 km east-southeast of the Oshika Peninsula, at a depth of 24 km [4]. The moment magnitude of the earthquake was 9.0, which was the largest among seismic records in Japan. Strong ground motion and tsunamis were generated by the earthquake, so that about 16,000 people died, about 2500 people are missing, more than 120,000 buildings were completely collapsed, and more than 280,000 buildings were partially collapsed [5].

The earthquake has many features compared with conventional destructive earthquakes. For example, duration of the main shock was very long, at about 6 minutes, and the seismic wave was transmitted to the whole area of Japan. Another feature was the very large tsunami. The maximum wave height was more than 9.3 m, but actual height was not clear because the observation point was damaged by the tsunami. The maximum water level height that was supposed from trace or watermark was more than 20 m, and the maximum run-up height was more than 40 m. About 90% of victims died due to drowning in tsunamis, and much equipment in industrial facilities were covered with sea water. Additionally, lots of aftershocks occurred, the number of aftershocks with a magnitude more than 5 was 779 as of April 30, 2012 [4].

3.2 Investigation method

An investigation regarding damage of lifts and escalators from the earthquake was mainly carried out by the Japan Elevator Association [6]. The investigation was started from July when aftershocks decreased, because restoration of lifts and escalators was a priority just after the earthquake. Target earthquakes for the investigation were the main shock and aftershocks more than JMA seismic intensity 5+ that occurred until June. Targets machines were lifts and escalators which members of the Japan Elevator Association inspected, but small freight lifts were excepted from the investigation. Existence of damage, edition of the Seismic Design Guideline and so on were investigated by a questionnaire. Contents of the questionnaire was determined based on examples of damage reported in the Kobe Earthquake in 1995.

3.3 Damage of lifts

As a result of the investigation by using the questionnaire, damage was found in 8,921 out of 367,912 cases, so the incidence ratio was 2.43%

Figure 1 shows incidence ratio by JMA seismic intensity scale. The JMA seismic intensity is calculated from ground acceleration during an earthquake considering frequency components, and the minimum level is 0, the maximum level is 7. As shown in Fig. 1, more than 1/4 of lifts that were installed in area of the JMA seismic intensity 7 were damaged.

Figure 2 shows damage of lift by parts. As shown in Fig. 2, entanglements of ropes accounted for 1/4 of total damage. The reason was that large areas in Japan including Tokyo where many buildings exist were affected by the earthquake. Vibration of ropes relates to height of a building, length of a rope, the ground condition and so on. For example, Tokyo is located on a sedimentary layer, and long period seismic waves are excited by the layer. In general, high-rise buildings and long wire ropes have long natural period, so that there are risks of resonance.

Then many damages by flooding also occurred. This is a one of the features of the Great East Japan Earthquake. Other mechanical structures were also damaged by large tsunamis [7].

In addition, a lot of damage that was caused by interaction with buildings such as entanglements of ropes, deformation of rails, damage of hoistway equipment and so on occurred. Close cooperation with structural engineers of buildings is strongly recommended to reduce the damage of lifts.

Falling of counterweight blocks occurred, similarly to in past destructive earthquakes. Although the numbers of falling counterweight blocks waere few, it may cause human damage. However no falling of counterweight blocks in lifts that were designed by applying Seismic Design Guideline issued in 2009 occurred. Therefore, the guideline was revised effectively.

Figure 3 shows relationship between edition of Seismic Design Guideline and incidence ratio. Incidence ratio decreased with the edition, thus revisions were effective.

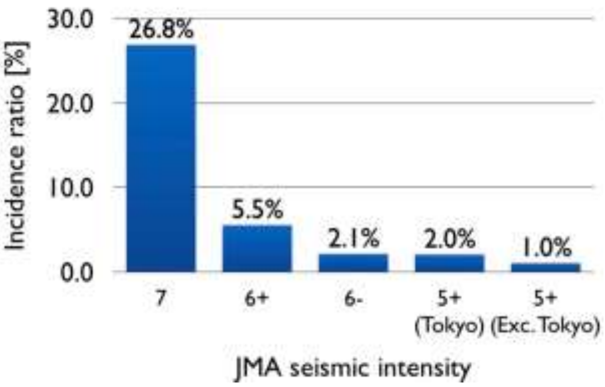

Figure 1 Incidence ratio of lift by Japan Meteorological Agency seismic intensity scale (Great East Japan Earthquake in 2011)

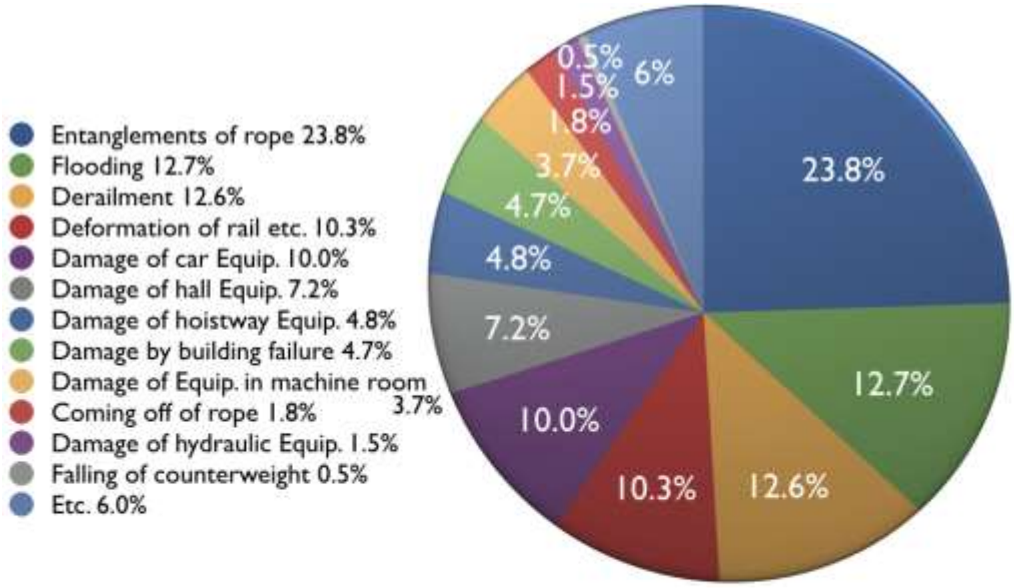

Figure 2 Damage of lift by cause (Great East Japan Earthquake in 2011)

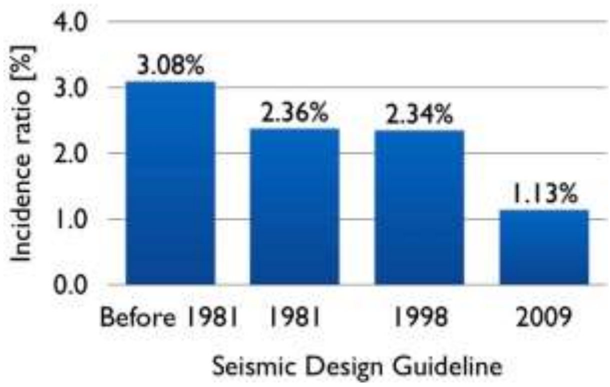

Figure 3 Relationship between edition of Seismic Design Guideline and incidence ratio of lift (Great East Japan Earthquake in 2011)

3.4 Damage of escalator

Damage of escalators was found in 1,598 out of 40,967 cases, so the incidence ratio was 3.90%

Figure 4 shows damage of escalators by parts. As shown in Fig. 4, damage by flooding, one of the features of the Great East Japan Earthquake, accounted for 1/5 of total damage. Apart from that, damage such as position shift and damage of landing plates occurred. This damage might be caused by interaction between buildings and escalators.

In addition, 4 escalators in shopping malls fell from floors of buildings. Although the number of falling escalators were few, it may cause human damage if passengers are on the escalators. Therefore, a project and revision of the guideline regarding fall accidents were carried out after the earthquake.

Figure 5 shows the relationship between edition of Seismic Design Guideline and incidence ratio. Damage incidence ratio of escalators before 1998 was small compared of escalators that were designed by applying Seismic Design Standard issued in 1998. On the other hand, the ratio of escalators after 2009 decreased.

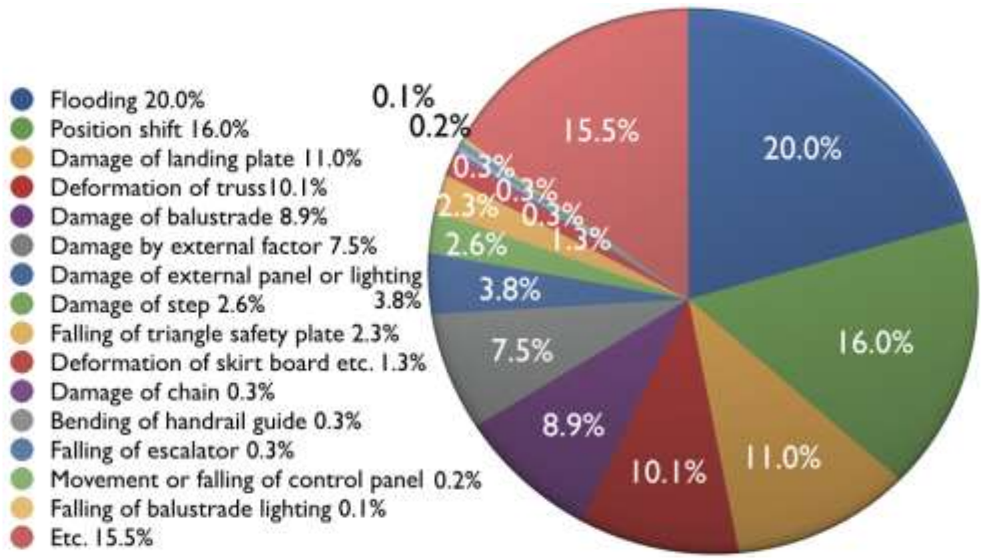

Figure 4 Damage of escalator by cause (Great East Japan Earthquake in 2011)

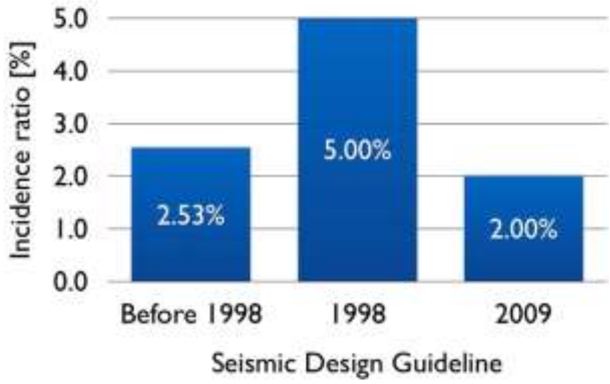

Figure 5 Relationship between edition of Seismic Design Guideline and incidence ratio of escalator (Great East Japan Earthquake in 2011)

4 DAMAGE FROM KUMAMOTO EARTHQUAKE IN 2016

4.1 Summary of earthquake

On April 14, 2016 at 21:26 JST, a strong earthquake having moment magnitude 6.2 occurred in Kyushu Region in the southwest part of Japan. The hypocenter of the earthquake was Kumamoto Prefecture, with a depth of 11 km. The JMA seismic intensity was 7, which is one of the largest level of intensity, but this was a foreshock. About 28 hours later, on April 16 at 1:25 JST, another strong earthquake having moment magnitude 7.0 occurred in same area, at a depth of 12 km. This was a main shock. The series of earthquakes caused the death of 228 people (this includes earthquake related-death). More than 9,000 buildings were completely collapsed, and more than 45,000 buildings were partially collapsed [8]. The features of the earthquake was strong ground motion and landslides. Industrial facilities in Kumamoto Prefecture were damaged by the earthquake, and the main cause of damage of mechanical structures was strong vibration [9].

4.2 Investigation method

The same investigation method as the Great East Japan Earthquake was applied, namely investigation using the questionnaire conducted by the Japan Elevator Association from June to July [10]. Target earthquakes for the investigation were the foreshock, the main shock and 3 aftershocks more than JMA seismic intensity 5+ that occurred in April.

4.3 Damage of lifts

As a result of the investigation by using the questionnaire, damage was found in 1,027 out of 95,424 cases, so the incidence ratio was 1.08%. This result was smaller than the Great East Japan Earthquake.

Figure 6 shows damage of lift by parts. As shown in Fig. 6, damage related to buildings such as entanglements of ropes, damage of rails, entrance halls and so on mainly occurred. Five cases of falling of counterweight blocks occurred, but these happened at lifts that were designed by using the Seismic Design Guideline issued in 1981 or before.

Figure 7 shows the relationship between edition of Seismic Design Guideline and incidence ratio. Incidence ratio decreased with the edition as well as the Great East Japan Earthquake, thus effectiveness of the revision was confirmed.

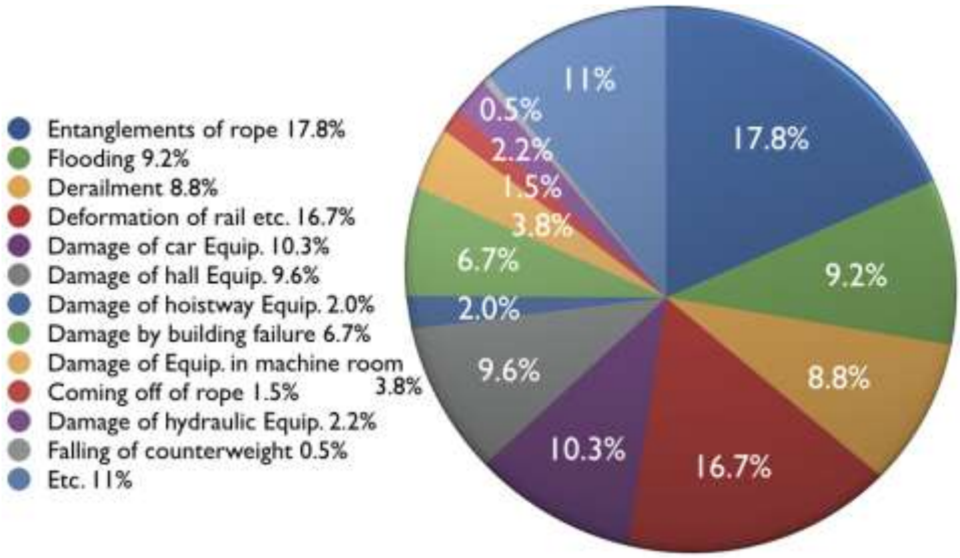

Figure 6 Damage of lift by cause (Kumamoto Earthquake in 2016)

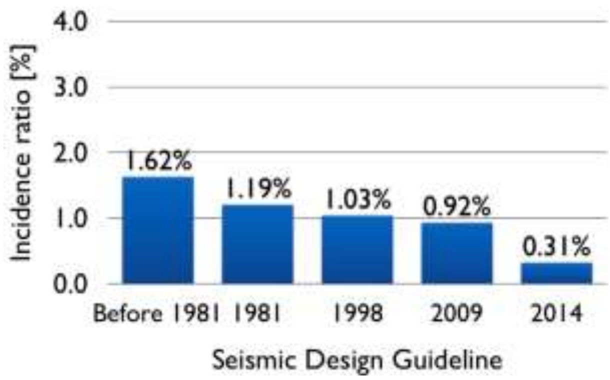

Figure 7 Relationship between edition of Seismic Design Guideline and incidence ratio of lift (Kumamoto Earthquake in 2016)

4.4 Damage of escalator

Damage of escalators was found in 330 out of 8,744 cases, so the incidence ratio was 3.77%

Figure 8 shows damage of escalators by parts. As shown in Fig. 8, damage mainly occurred in landing plates, external panels or lighting, and this damage was related to interaction with building. In addition, no fall accident of escalators occurred.

Figure 9 shows relationship between edition of Seismic Design Guideline and incidence ratio. Although incidence ratio of escalators after 2014 was small, the ratio increased with the edition. In order to clarify reason of this result, investigation in consideration of buildings is needed.

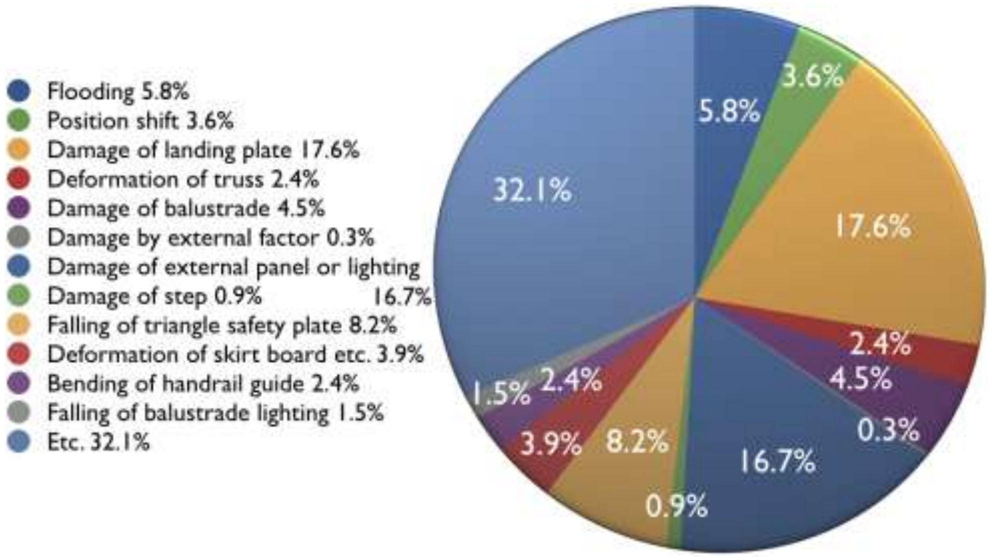

Figure 8 Damage of escalator by cause (Kumamoto Earthquake in 2016)

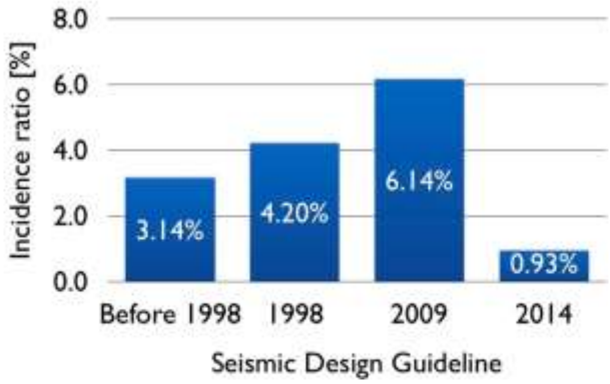

Figure 9 Relationship between edition of Seismic Design Guideline and incidence ratio of escalator (Kumamoto Earthquake in 2016)

5 CONCLUSION

In this paper, changes of the Seismic Design Guideline in Japan, and investigation results regarding damage of lifts and escalators from large earthquakes were reported. The results are summarized as follows;

- Seismic Design Guideline of Japan was revised according to actual damage from large earthquakes. From the investigation results of the Great East Japan Earthquake and the Kumamoto Earthquake, the revision was basically effective to improve seismic reliability of lifts and escalators

- Lifts and escalators are generally installed in buildings. Therefore, close cooperation with structural engineers of buildings is strongly recommended to reduce the damage of lifts and escalators.

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BIOGRAPHICAL DETAILS

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MLIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MLIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Mr. Motoo Shimoaki is a managing director of the Japan Elevator Association. He has long experience as an engineer of elevator company.

Dr. Keisuke Minagawa is an associate professor of Saitama institute of technology and is a chair of the Technical Committee of Lifts, Escalators and Amusement Facilities held in JSME (Japan Society of Mechanical Engineers). He has been an evaluator of lift systems and mechanical car parking systems since 2015. He is also an expert of seismic isolation and vibration control.

Robots, Non-human Passengers

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Keywords: lifts, robots, traffic handling

Abstract. Lifts are increasingly being called upon to transport robots between floors in multi-story buildings. The robots that are presently available place special demands on lifts and those demands affect traffic handling. The special demands are explained and the impact of those demands on waiting time and transit time are reviewed using simulation.

1 INTRODUCTION

1.1 Robot types

There are two principal types of robots; Industrial Robots and Service Robots. Industrial robots are used for manufacturing [1]. A Service Robot is defined by the International Organization for Standardization (ISO) as a robot "that performs useful tasks for humans or equipment excluding industrial automation applications" [2].

Service Robots are further subdivided into three categories by the International Federation of Robotics (IFR) [3]:

1. Professional service robots
2. Service robots for domestic/household tasks
3. Service robots for entertainment

Service robots for domestic/household tasks are such things as robotic carpet cleaners. Service robots for entertainment are essentially toys. Therefore, this paper addresses only professional service robots.

While there are many types of professional service robots, including some that milk cows and others that have military applications, there is a subset of professional service robots that will ride in lifts with humans. ISO 13482 further defines these types of robots as "Mobile Servant Robots" [4].

Mobile servant robots are classified as either Type 1.1 or Type 1.2 based on the following characteristics:

Type 1.1: small AND light weight AND slow AND no manipulator.

Type 1.2: large OR not light weight OR fast OR with manipulator.

1.2 Building types where robots use lifts

There are four building types where mobile servant robots are being applied in increasing numbers. These building types are hotels, office buildings, residential buildings, and hospitals.

In hotels, servant robots are being used for room service deliveries and for the delivery and movement of housekeeping carts.

In office, buildings robots are delivering packages and mail from sources outside the building as well as interoffice correspondence.

The growth of e-commerce has caused an increase of package deliveries to multi-story residential buildings. Robots are being used to make the final delivery from the lobby to the residential unit.

Hospitals have used pneumatic tube systems for delivery of medicines and the transport of medical records. Pneumatic tube manufacturers are now offering robots as an alternative to tubes [5].

2 GENERAL SAFETY STANDARDS FOR ROBOTS

ISO 13482 establishes safety requirements for personal care robots [4]. This standard identifies 53 hazards that need to be addressed through risk assessment. This standard establishes Performance Levels for the safety-related control functions. Performance Levels (PL) are defined in ISO 13849-1:2015 Safety of Machinery—Safety-related parts of control systems [6].

Both Type 1.1 and Type 1.2 Mobile Servant Robots are required to achieve Performance Level (PL) *d* for their emergency stop function. For all other safety functions Type 1.1 robots much achieve PL *b* while Type 1.2 robots must achieve PL *d*.

Performance Level b indicates that that the Probability of a dangerous failure is between 1 X 10^{-5} and 3 X 10^{-6}.

Performance Level d indicates that that the Probability of a dangerous failure is between 1 X 10^{-6} and 1 X 10^{-7}.

3 ROBOT CHARECTERISTICS THAT AFFECT LIFTS

3.1 Mass & Size

There are two basic types of mobile servant robots that are manufactured by several manufacturers that need to use lifts to be effective. One type is a high mass vehicle that is referred to as a tug by one manufacturer [7]. The other type of robot is a low mass unit used for room service.

The tug type of robot has a payload of 453 kg. The tug and its lead acid batteries also have significant mass. It is 1164 mm long and 570 mm wide. It has a turning envelope of 1270 mm. The turning envelope is a circle with a diameter of 1270 mm. The area of this envelop is 1.27 m^2 [7]. This is a Type 1.2 robot.

The room service robot has a total mass, including payload, of 50 kg. This robot is cylindrical and its diameter is 500mm. The turning envelope is also 500 mm which makes the area of the envelope 0.2 m^2 [8]. This is a Type 1.1 robot.

The room service robot is designed to ride in the lift with human passengers. The mass, size, and turning envelop of the tug type robot needs a much larger lift. Consideration should be given limiting the access of a tug type robot to service lifts.

3.2 Velocity

Both types of robots have velocities of 0.76 m/s. Humans walking to a lift can be assumed to have a walking speed of 1.0 m/s [9]. Walking speed is a component of loading time.

3.3 Kinetic energy

Kinetic Energy is defined by the following equation [10]:

$$KE = \frac{1}{2}mv^2 \tag{1}$$

Where: KE represents Kinetic Energy

m represents mass

v represents velocity

The ASME A17.1 code has a kinetic energy limit and velocity limit for Dumbwaiters with Automatic Transfer Devices [11]. An automatic transfer device is defined as "a power-operated mechanism that automatically moves a load consisting of a cart, tote box, pallet, wheeled vehicle, box, or other similar object from and/or to the car". The kinetic energy limit is 40 J and the velocity limit is 0.5 m/s during unloading. These limitations do not apply directly to robots riding with human passengers as passengers do not ride in dumbwaiters. However, they give some guidance in the lack of a robot specific standard.

In the case of a tug type robot with a total mass of 600 kg (453 kg payload and 147 kg estimated tug mass), the loading speed would need to be reduced 0.365 m/s during loading and unloading to comply with the 40 J limitation.

A room service robot operating at 0.76 m/s does not exceed the 40J limit. However, it does exceed the 0.5 m/s velocity maximum. Therefore, the maximum velocity during loading and unloading should be limited to 0.5 m/s.

Based on kinetic energy and velocity limits, the loading and unloading times for robots should be greater than the loading and unloading time for humans.

Data needs to be gathered by observing loading operations with robots operating at these speeds. In the absence of this data it would seem logical to add 1.2 seconds to both loading and unloading times when assessing the impact of robots on traffic handling performance. These increased times will increase waiting and transit times.

3.4 Personal Space

Personal Space, as it relates to lifts, defines the number of passengers that will ride in a lift at one time. CIBSE Guide D suggests that an adult male will occupy a space of 0.21 m^2 [9]. This is based on the male being a European or North American and does not include personal space.

Barney proposes that the design capacity of a lift should be based upon approximately 0.263 m^2 per person [12].

Personal space is space between humans. Robots are not humans. There is some research that indicates humans do not view robots as social entities (humans) [13]. The spatial distance that humans will require with robots is probably affected by the same factors that affect spatial distance between humans such as age and culture.

Research is needed in this area. However, in the absence of data, a starting point might be to add a buffer zone of 150 mm around a room service robot. For example, a cylindrical robot with a diameter of 500 mm would occupy, 0.5 m^2 (space diameter of 800 mm).

Personal space for tug type robots should be different because they will need large lifts due to their mass, physical dimensions, and turning envelopes. Tug robots will not be considered in the traffic section of this paper.

4 TRAFFIC EFFECTS

Room service robots are being installed in an existing 4 Star hotel in California. A study of the impact of these robots on passenger traffic was conducted. The following are the building, lift system, and passenger characteristics used for this traffic study.

Building:
- Floors: 25
- Rooms: 510, Located on Levels 4 – 25
- Dispatch Lobby: Level 1

Occupancy: 440 Guests based on 86% occupancy and 1 person per room.

Lift System:
Number of Cars: 4
Capacity: 1600 kg
Speed: 2.5 m/s
Dispatch Algorithm: Estimated Time of Arrival (ETA).
Door Type: Center Opening
Door width: 1066 mm.
Car Loading: 60% by Volume

Passengers:
Humans:
Loading Time: 1.2 s
Unloading Time: 1.2 s
Area: .26m²
Robots (room service type):
Loading Time: 2.4s
Unloading time: 2.4 s
Area: 0.5 m²

Traffic Template: Peters (CIBSE) Hotel

Figure 1 below graphically represents the Passenger Demand levels of the Peters (CIBSE) Hotel traffic when applied to the occupancy of the subject hotel.

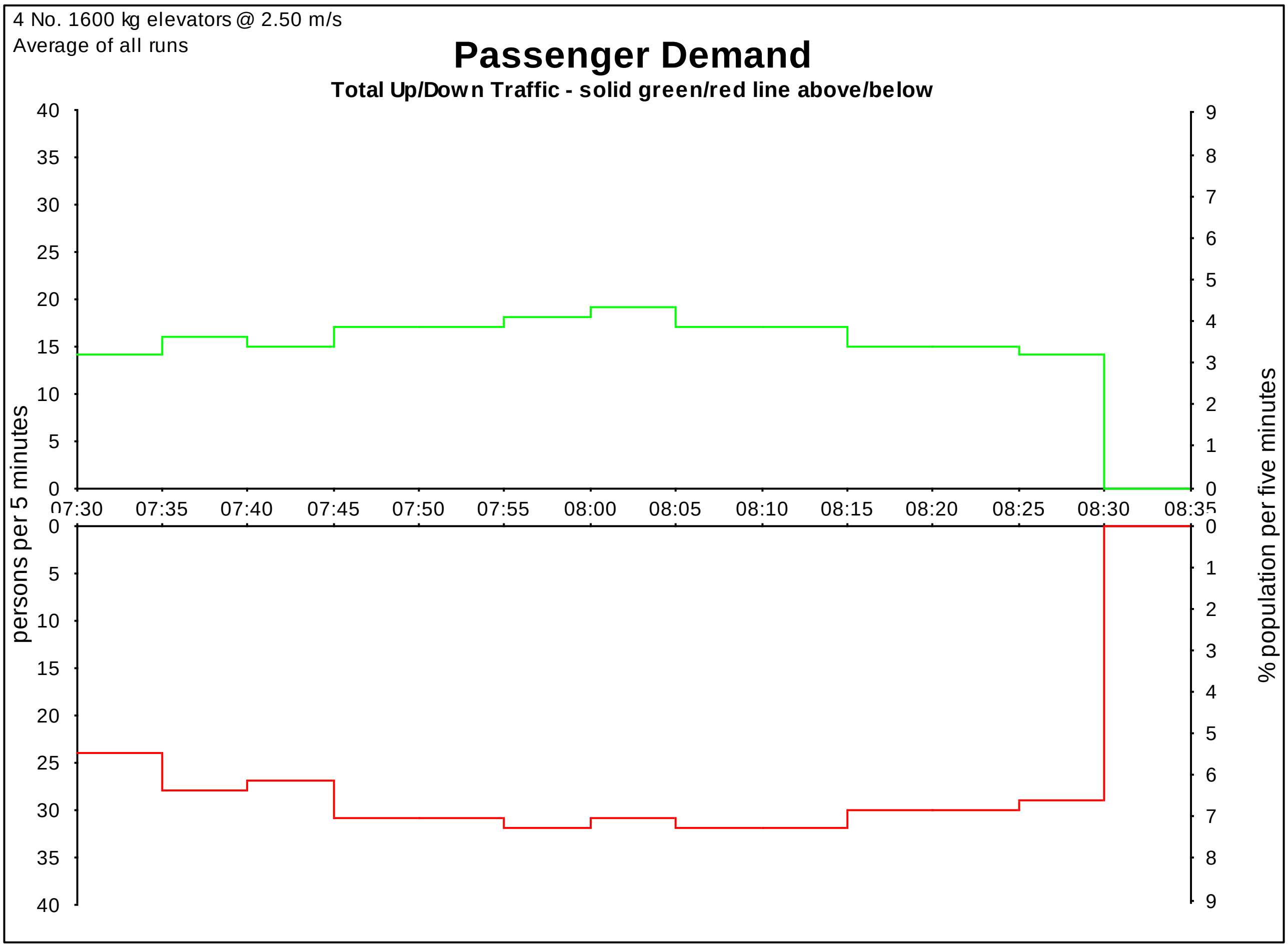

Figure 1 Passenger Demand, Peters (CIBSE) Hotel Template

Figures 2 and 3 show the results of traffic simulations using a Peters (CIBSE) Hotel Template with no robots installed. Figure 2 shows Waiting Times while Figure 3 shows Transit Times.

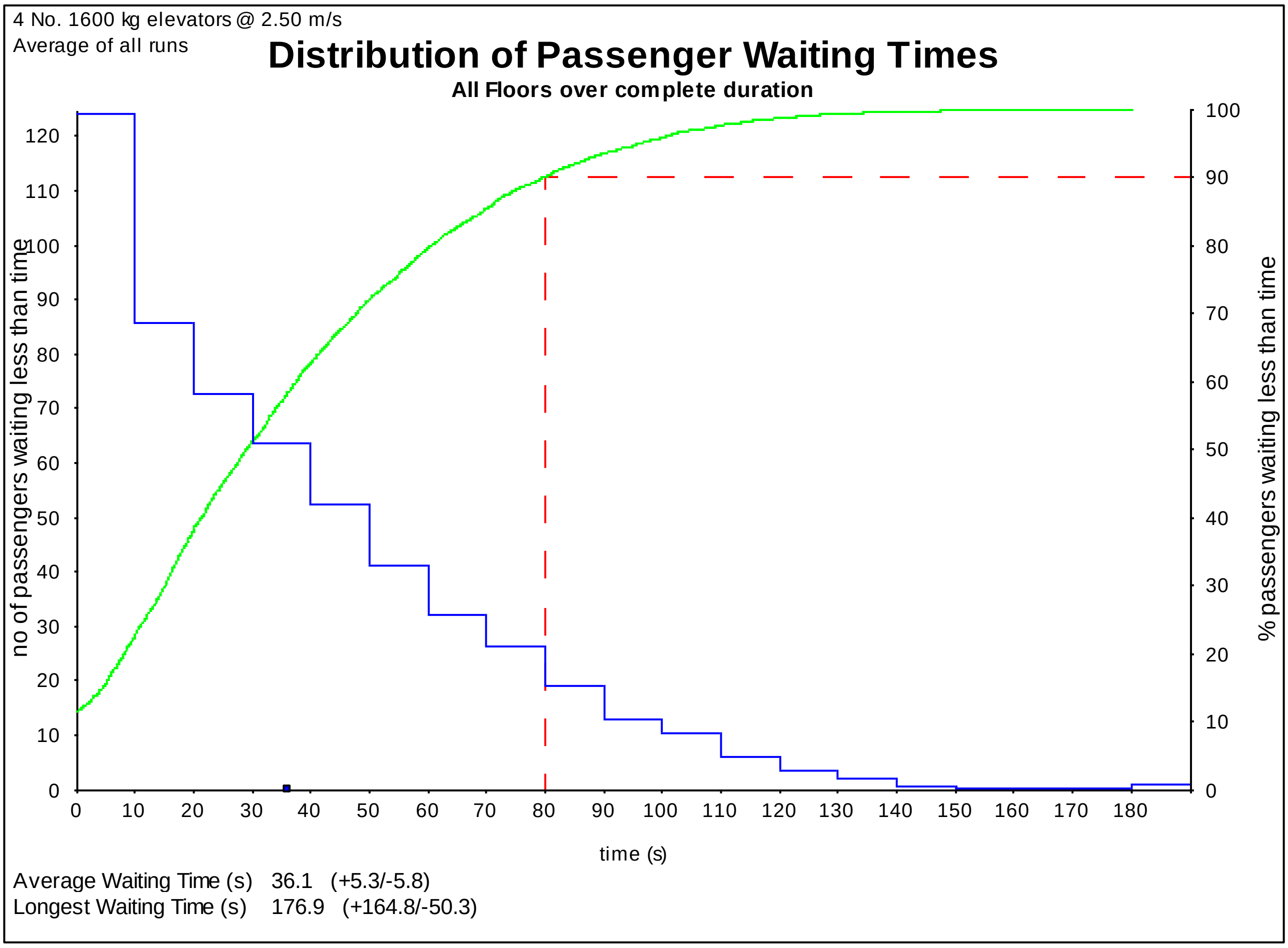

Figure 2 Waiting Times without robots

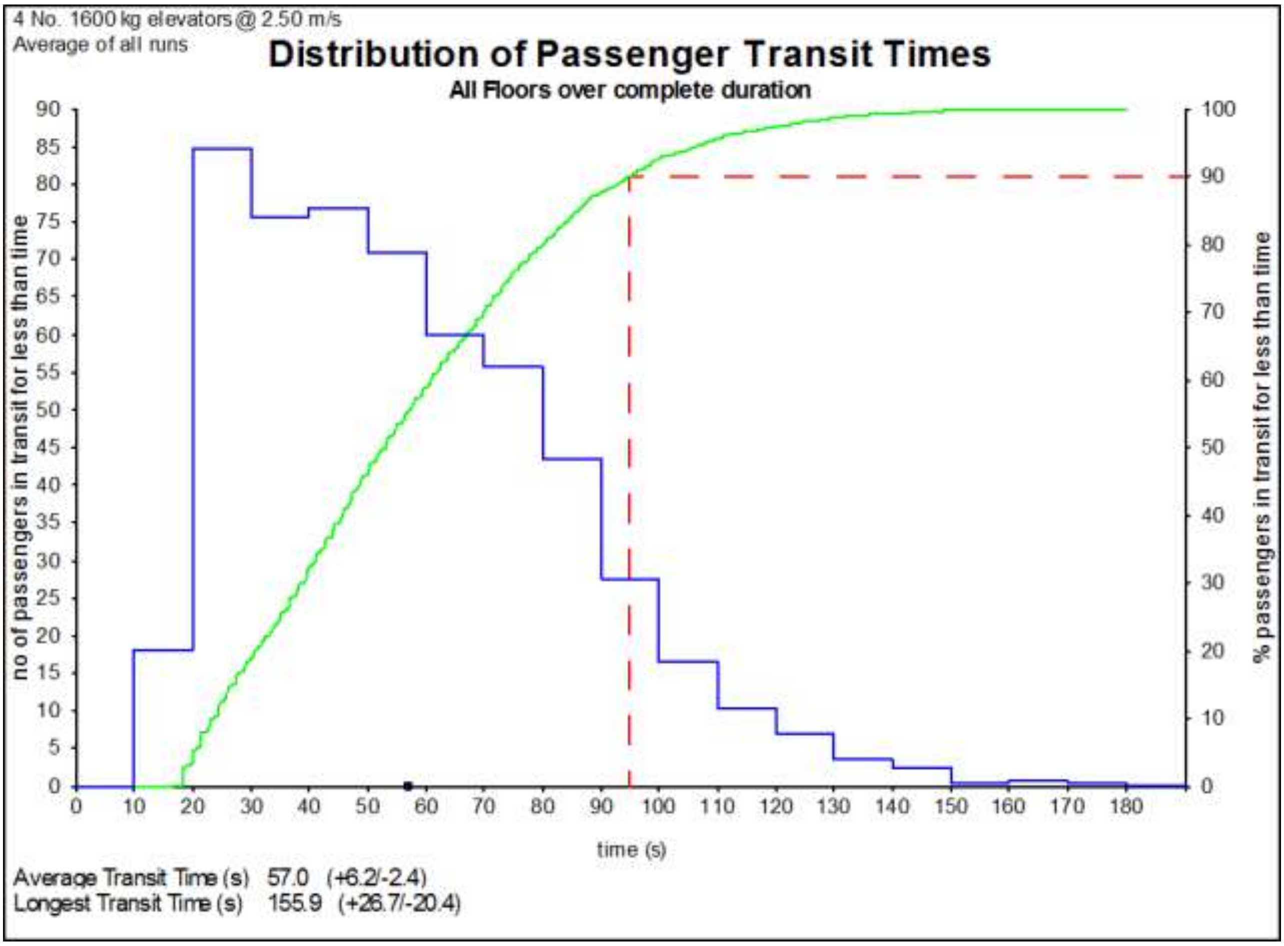

Figure 3 Transit Times without robots

Figures 4 and 5 show the results of traffic simulations using a Peters (CIBSE) Hotel Template with one additional person making a room service delivery. The one person makes one delivery round trip every 5minutes. Figure 4 shows Waiting times while Figure 5 shows Transit Times.

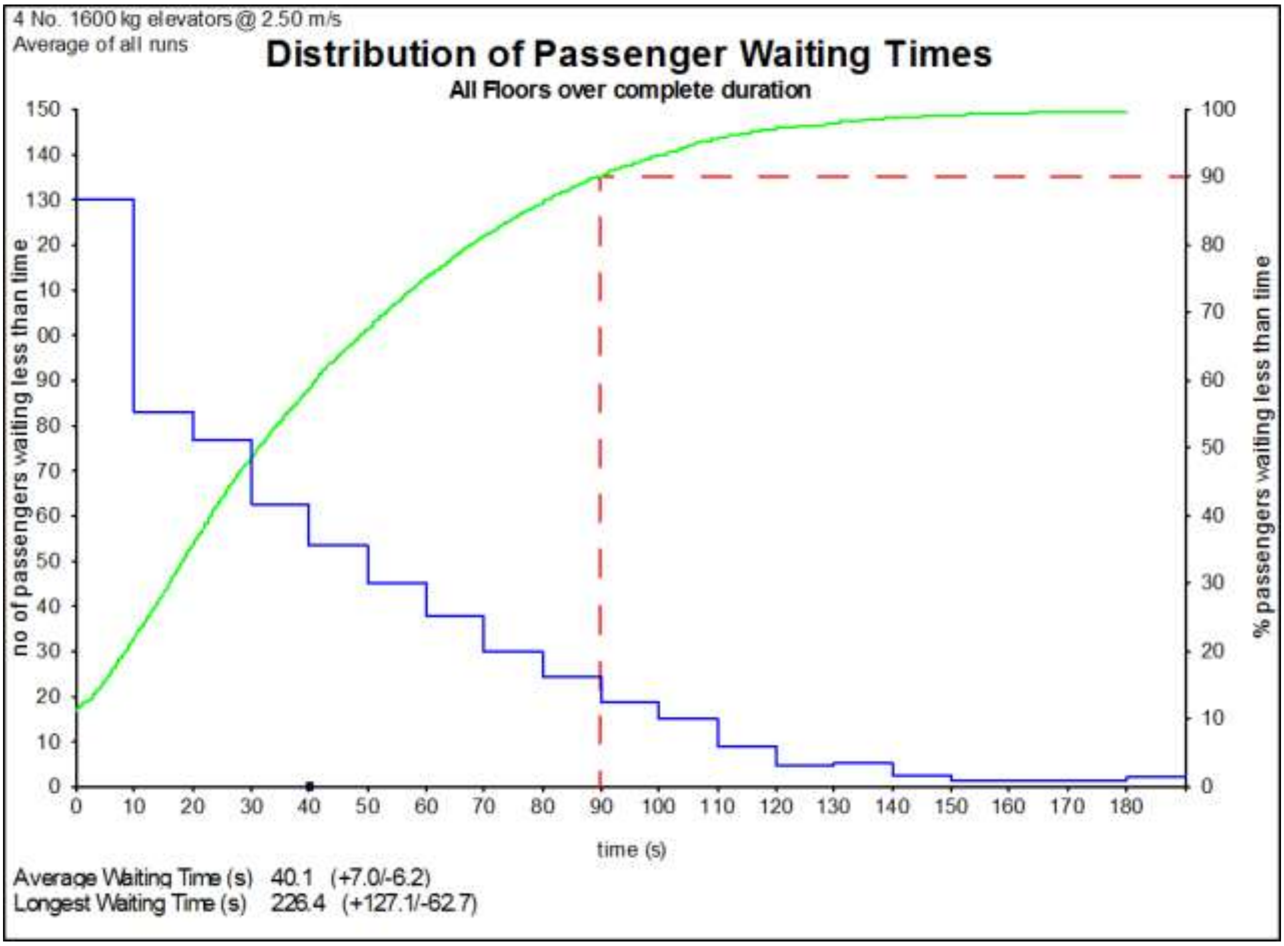

Figure 4 Waiting Times with one additional human passenger

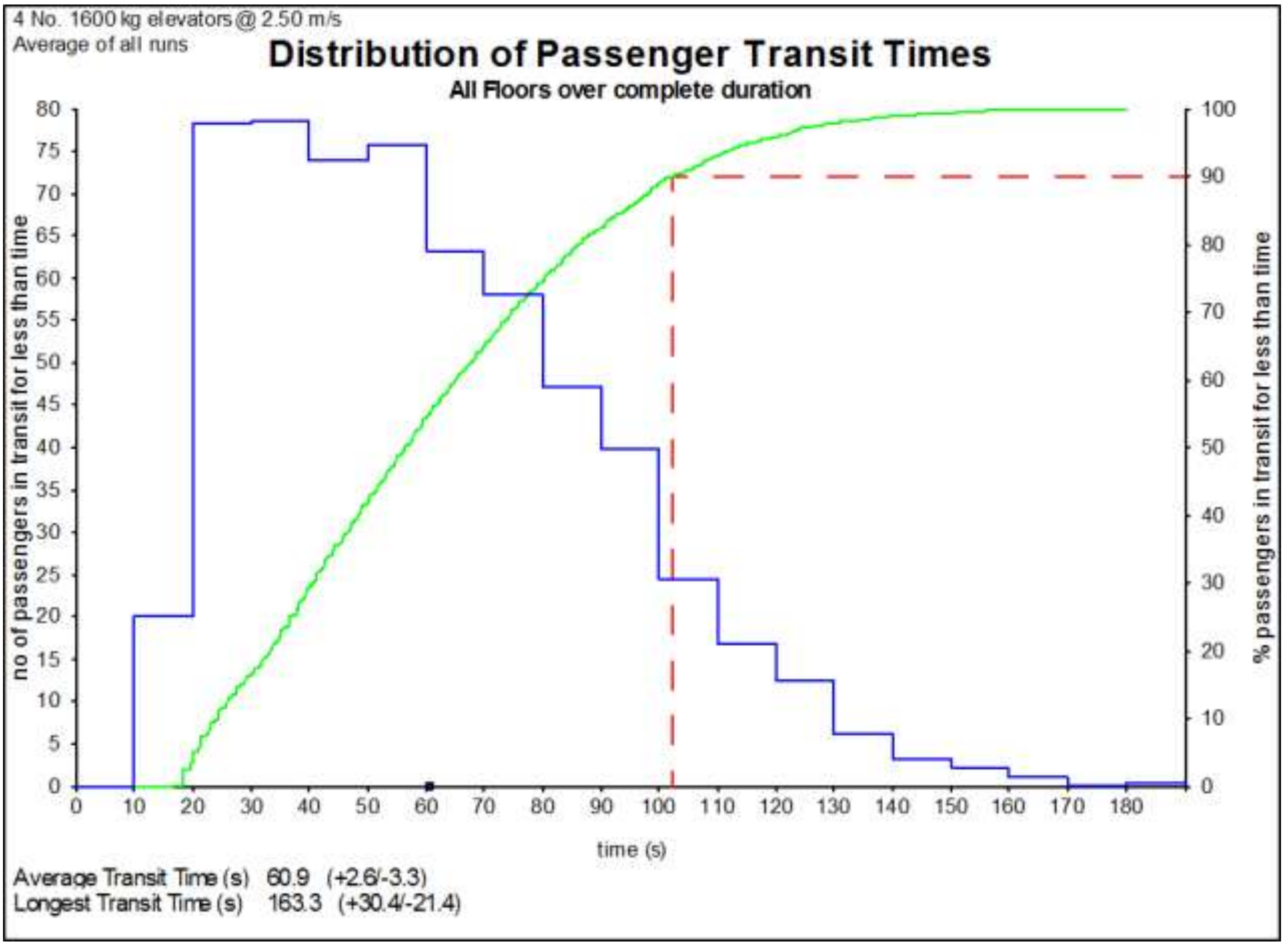

Figure 5 Transit Times with one additional human passenger

Figures 6 and 7 show the results of traffic simulations using a Peters (CIBSE) Hotel Template with one robot making a room service delivery. The one robot makes one delivery round trip every 5minutes. Figure 6 shows Waiting times while Figure 7 shows Transit Times.

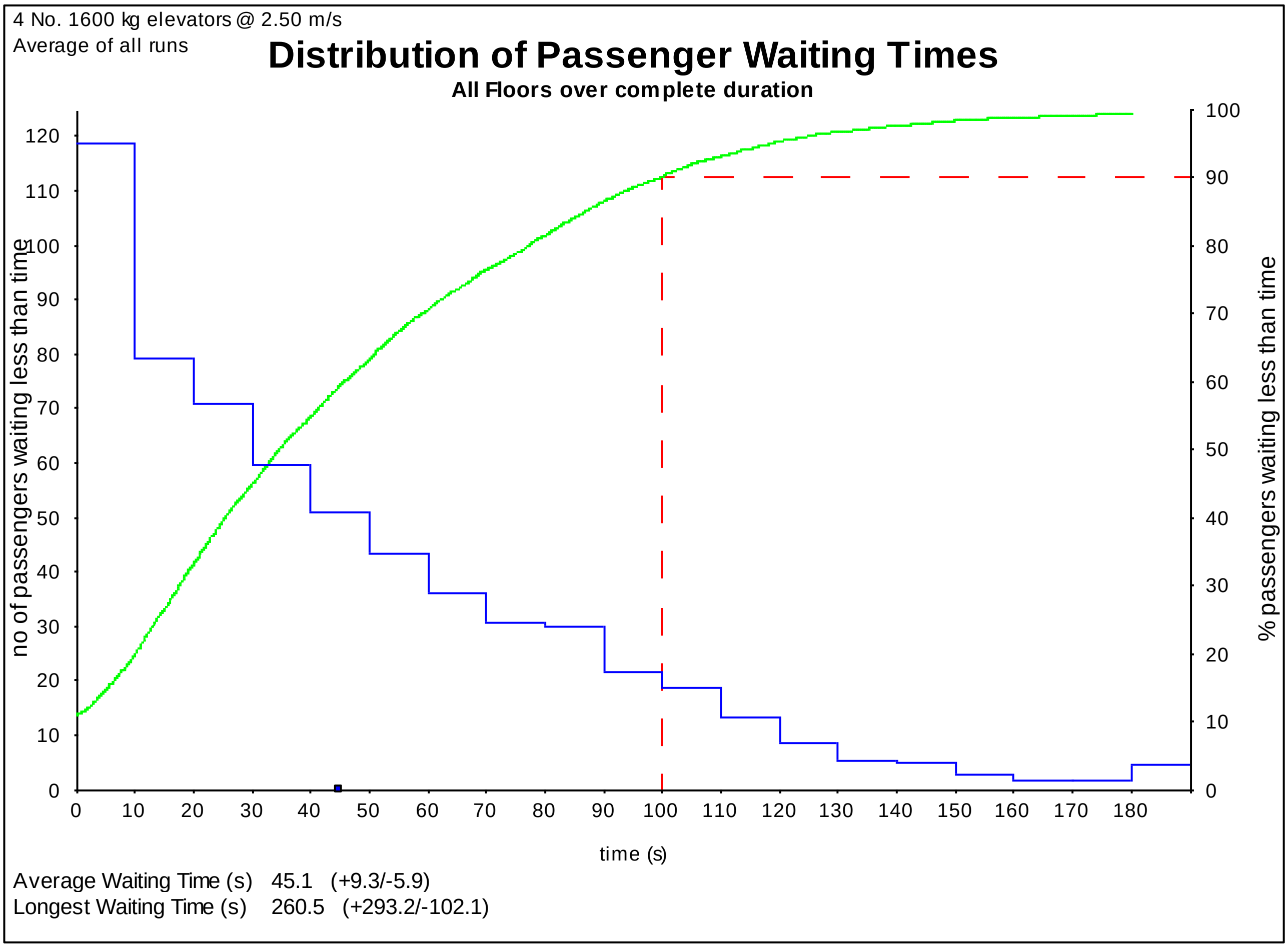

Figure 6 Waiting Times with one robot

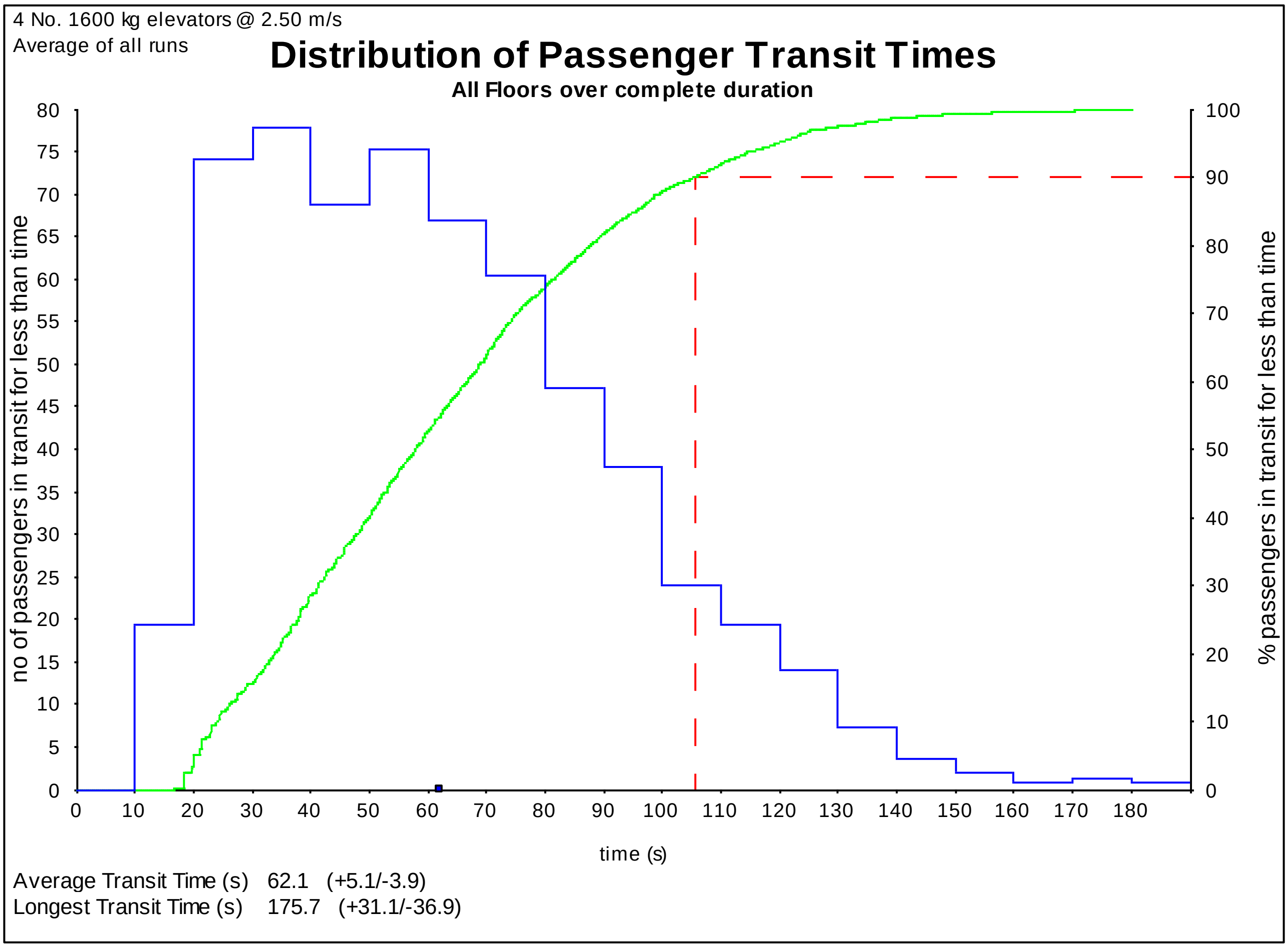

Figure 7 Transit Times with one robot

Table 1 summarizes these results.

Table 1 Waiting Times, Transit Times and Times to Destination

	Waiting Time	Transit Time	Time to Destination
No Robots	36.1s	57.0s	93.1s
With 1 additional person	40.1s	60.9s	101.0s
With 1 robot	45.1s	62.1s	107.2s
Additional time for 1 robot compared to 1 person	**5.0s**	**1.2s**	**6.2s**

It should be noted that one robot will increase waiting time by 12.5% more than 1 person due to "personal space" and loading/unloading time.

5 CONCLUSIONS

Robots should be considered as a new class of passenger because they do not yet behave in the same manner as humans.

At present, their speed must be controlled during loading and unloading to either control kinetic energy or velocity. With continuing improvements in machine vision, robots may become better at avoiding collisions with people and property than humans and these restraints could be relaxed.

The physical shape of robots is not the same as humans and so the floor space they occupy is different from humans.

More research is needed to understand the human interaction with robots as passengers. We need to know how much personal separation humans need between themselves and robots.

The speed and personal space characteristics of robots have a negative effect on the traffic handling capacity of lift systems. If robots are planned for a new building, the proposed lift system should be designed acknowledging these effects. If robots are proposed for an existing building, a traffic study should be performed that demonstrates the impact of the robots.

The number of robot installations is growing. Lift traffic consultants need to understand the impact of robots on traffic so they can properly advise their clients.

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BIOGRAPHICAL DETAILS

Rory Smith is Visiting Professor in Lift Technology at the University of Northampton. He has over 49 years of lift industry experience during which he held positions in research and development, manufacturing, installation, service, modernization, and sales. His areas of special interest are Robotics, Machine Learning, Traffic Analysis, dispatching algorithms, and ride quality. Numerous patents have been awarded for his work.

Study on Compressive Deformation of Escalator Truss During Earthquakes Considering Large Deformation

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Keywords: Escalator, Finite element method, Elasto-plastic analysis, Buckling, Quake-resistance standards

Abstract. Four fall accidents of escalators occurred utilized in three shopping centers during Greatest East Japan Earthquake in 2011.Based on the fall accidents, the quake-resistance standard of the escalator was reviewed in Japan. In the new quake-resistance standard, inter-story deflection assumed during earthquakes was set larger than before. It is conceivable that an existing escalator receives compressive load from a building. Therefore, it is necessary to investigate how the escalator truss behaves due to compressive load. From the above background, this study builds a model of the escalator truss that is subjected to compressive load based on results of a compression experiment of the escalator trusses of actual machine size. Elasto-plastic analysis was performed using the finite element method, and the state of deformation during compression was confirmed. The effectiveness of the analysis model was compared with the compression experiment of the escalator truss of the actual size. It is considered that the analytical model can reproduce the trend of the load-displacement curve.

1 INTRODUCTION

Escalators are generally installed by attaching L-shaped steels called support angle irons at both ends and hooking it on a building beam. The escalators have truss-structure that one end is fixed and the other end is unfixed to prevent breakage, when a building is deformed by an earthquake. However, four fall accidents of escalators utilized in three shopping centers occurred during Greatest East Japan Earthquake in 2011[3].The reason is that the non-fixed parts were detached due to large inter-story deflection than assumption. Based on the fall accidents, the quake-resistance standard of the escalator was revised in Japan. In the new quake-resistance standard, inter-story deflection assumed during earthquakes was set larger than before [4]. Therefore, it is possible to prevent fall accidents, but on the other hand it is conceivable that an existing escalator receives compressive load from a building. However, it is difficult to secure a sufficient clearance between the building beam and the escalator, and when the large inter-story deflection occurs, the escalator truss may be greatly deformed by compression load and may cause troubles in safety. Also, since the structure of the escalator truss has no fixed provision, it differs according to each company. Therefore, it is necessary to investigate how the escalator truss behaves due to compressive load. From the above background, this study builds a finite element analysis model of the escalator truss that is subjected to compressive load based on results of a compression experiment of the escalator trusses of actual machine size. In this study, a simple analysis model is created, welds are made as one body, and material properties are uniformly decided. The validity of the analysis model is investigate by comparing with the compressive experiment of the escalator truss of the actual size.

2 COMPRESSION EXPERIMENT OF THE ACTUAL SIZED ESCALATOR TRUSS

2.1 Outline of experiment

As part of the building standards development promotion project in 2014, a compression experiment of the actual sized escalator truss was carried out [1]. Experiments confirmed the deformation behavior of the escalator truss when receiving a compressive load from the building beam during the earthquake. In the structure of the escalator truss, it is conceivable that buckling will occur when subjected to enforced displacement in the longer direction. Therefore, it is considered that the truss members deform such as buckling, and the strength of the truss decreases greatly. Therefore, even after the member is deformed, it is necessary to confirm whether truss member can hold device weight and movable load or not.

2.2 Test body

In order to investigate the behavior of deformation due to the difference in the structure of the escalator truss experiments were conducted with 7 test bodies of 4 patterns. Differences in deformation behaviors due to differences in structure could be confirmed. In this report, three pattern of experimental results are reported. Table 1 and 2 show common specifications of each test body. Main material is Japanese Industrial Standard (JIS) SS400 [2]. The lift height of the escalator was 3 [m], and the test bodies close to practical use. Figure 1 shows the test body. Only the truss was included in the test body, not included the escalator's internal equipment (step, handrail, drive unit and so on). Weight of internal equipment is reproduced by hanging the dummy weights.

Table 1 Parameter of escalator

Height [mm]	Span [mm]	Truss width [mm]	Incline [°]	Main Material	Support
3000	9476	1500	30	JIS SS400 (carbon steel)	Top: Fixed Bottom: Non fixed

Table 2 Parameter of JIS SS400

Types of symbol	Yield stress [MPa]		Tensile strength [MPa]
	Thickness of steel [mm]		
	t ≦ 16	16 < t ≦ 40	
JIS SS400	245 and over	235 and over	400～510

Figure 1 Test body

2.3 Experiment method

Figure 2 shows the experimental outline. The top support angle and the top frame were fixed so that the escalator truss was prevented from floating up during compression. The bottom part of the escalator truss was constructed to slide in the longer direction so that it can be compressed in the longer direction. A load cell was installed at the bottom end and the reaction force was measured. Table 3 shows the experimental process. Compression and unloading were given step by step, and the influence by repeated load was confirmed. Finally, enforced displacement was given up to 200 [mm].

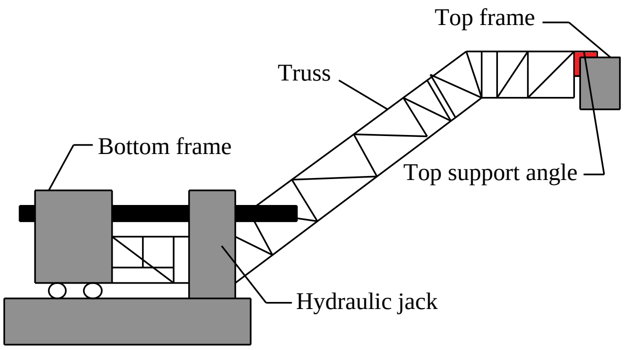


Figure 2 Experiment outline

Table 3 Experiment step

Step1	Press to 40 mm
Step2	Unloading
Step3	Press to 80 mm
Step4	Unloading
Step5	Press to 200 mm
Step6	Unloading

2.4 Experiment result

Figure 3 shows the appearance of deformation, Figure 4 shows the relationship between the enforced displacement and the reaction force of the truss. Immediately after the start of compression, all trusses underwent elastic deformation along with an increase in displacement. After that, it buckled and the load sharply decreased. However, there was difference in buckling load and transition of load. It is considered that there is no effect of repeated loads given to 40 [mm] and 80 [mm] for all trusses. Even if displacement was given up to about 200 [mm], all trusses were self-sustaining without falling.

Pattern A

Pattern B

Pattern C

Figure 3 Deformation of experiment

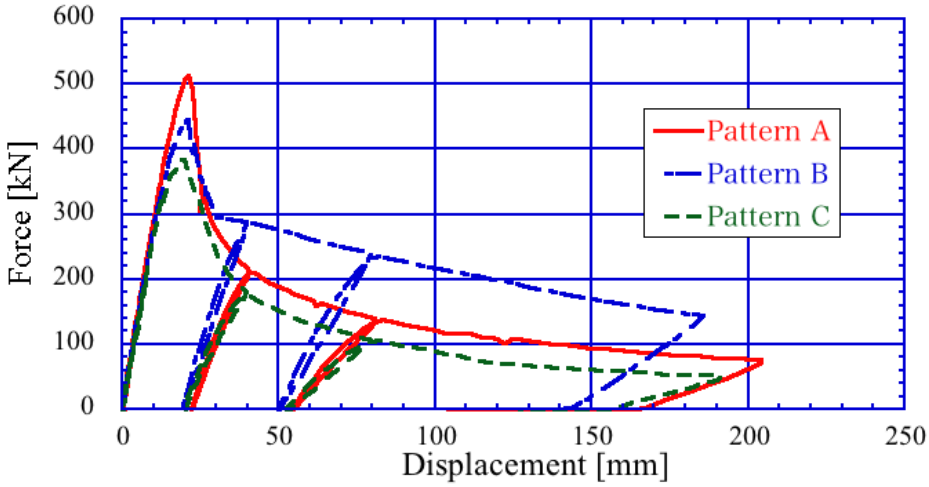


Figure 4 Reaction force of compression of experiment

3 FEM ANALYSIS

3.1 Analytical objective

An analytical model is created to simulate the compression experiment and elasto-plastic analysis is performed by using the the finite element method. In this report, the analysis model is made and it is evaluated by comparing load-displacement curve and deformation mode.

3.2 Analytical model

In this report, to create simple analysis model is aimed. Many escalator trusses are made of welded L-shaped steel, but analysis modelconsiders welded steel as one unit. Properties of steel are set uniformly regardless of the shape of member. In addition, analysis using bilinear models was performed and the same plastic factor were used. For the yield stress, two patterns were analyzed. Simulation 1 is yield stress of JIS standard. Simulation 2 is yield stress according to experimental result. In the experiment, the weight of the internal equipment was reproduced by hanging weights, but in the analysis, it is reproduced by applying the load to the member. Table 4 and 5 shows analysis conditions. ANSYS Workbench 16.0 was used as analysis software. It has a static structure and the solver is Mechanical APDL. The element used solid.

Table 4 Parameter of simulation

Truss	Incline	Element	Material property	support method	Load condition
Height : 3000mm Span : 9476mm width : 1500mm	30 °	Solid	Bilinear model Young's modulus:206GPa Plastic factor:1450MPa	Top: X,Y,Z fixed Bottom: Y,Z fixed	(1) Linear pressure (2) X 200mm (3) Unloading

Table 5 Parameter of yield stress

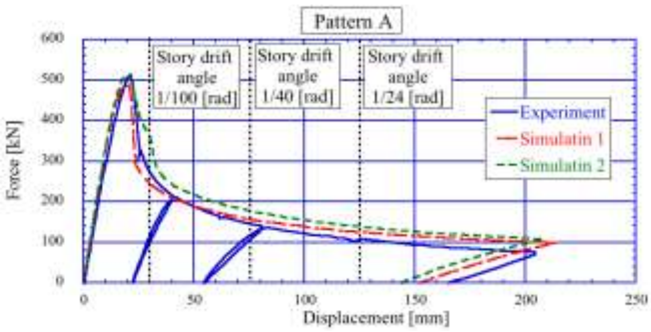
Yield stress [MPa]	Pattern A	Pattern B	Pattern C
Simulation 1 **JIS standerd**	245	245	245
Simulation 2 **adjustment**	290	285	195

3.3 Analytical method

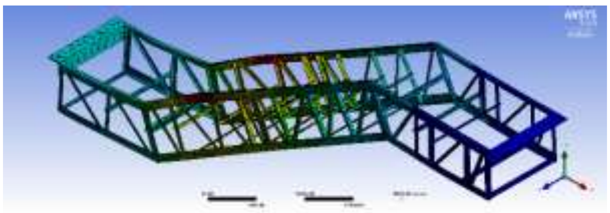
The analysis model simulates the experiment. The escalator truss was fixed the top end and enforced displacement of 200 [mm] was given. A story drift angle of the escalator at the time of the earthquake is determined by the quake resistance standard. the story drift angle includes 1/100 [rand], 1/40 [rad], 1/24 [rad], and so on. When not obtained by structural calculation, it is necessary to consider 1/24 [rad] or more. Analysis was done up to 200 [mm] beyond that values. The load-displacement curve is obtained by measuring the reaction force at the bottom end and deformation of the escalator truss.

3.4 Analytical result

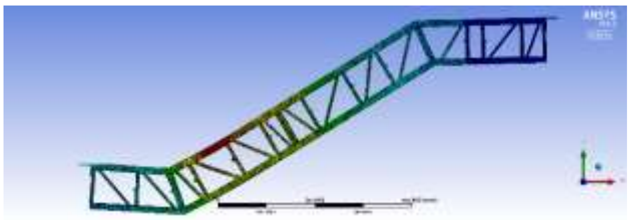
Figures 5, 6, and 7 show the analytical results. Upper left shows the load-displacement curve, the solid line shows the experiment result and the others show the analysis result. The upper right shows the whole figure, the lower left shows the side view, the lower right shows the top view. The yield stress of the material used in the experiment was higher than the JIS standard because the JIS standard indicates the lower limit value. Therefore, in Patterns A and B, the buckling loads of the analysis results using the JIS standard are smaller than the experiment results. However, in Pattern C, the buckling load of the analysis result using JIS standard is larger the experiment result. Pattern C might be influenced by the initial misalignment. In the three patterns, by adjusting the buckling load of the analysis results to the experiment result, the load transition after buckling can be reproduced roughly. The state of deformation focuses on the lower end, and it can be roughly reproduced.



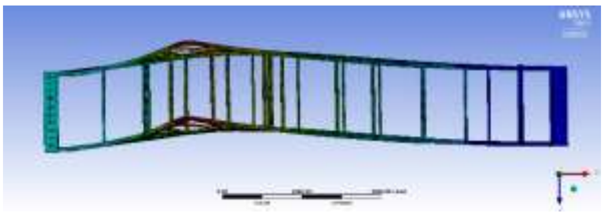
(a) Force-Disp. curve



(b) General view

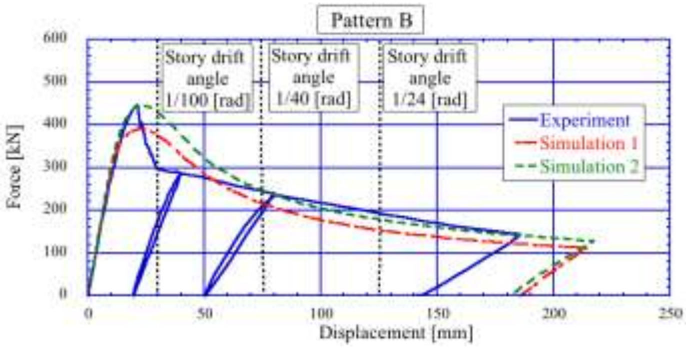


(c) Side view

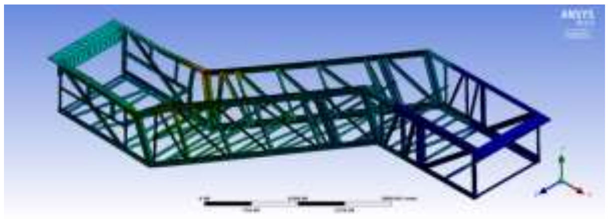


(d) Top view

Figure 5 Analytical results of pattern A



(a) Force-Disp. curve

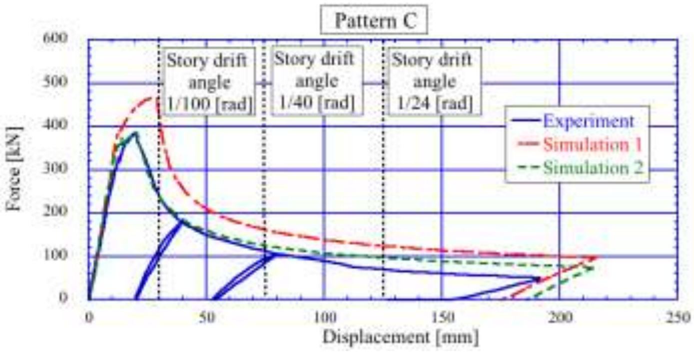


(b) General view

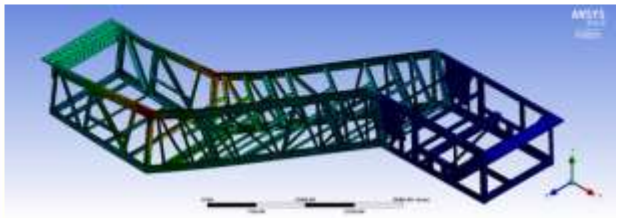
(c) Side view

(d) Top view

Figure 6 Analytical results of pattern B



(a) Force-Disp. curve



(b) General view

(c) Side view

(d) Top view

Figure 7 Analytical results of pattern C

4 CONCLUSION

In this study, a simple analytical model that considered welded steel as one unit and properties of steel are set uniformly regardless of the shape of member has been developed and analyzed, also the validity was compared with the experimental result. Even with a simple analysis models, they can analyze considering buckling and unloading. It is confirmed that the analysis model can reproduce the experiment roughly. In the analysis using the finite element method, results are often adjusted. Even the analysis result using the JIS standard in this analysis model is roughly reproducing the experiment result. It is considered that the analysis model can propose a thing sufficient enough for safety margin evaluation of escalator truss in advance.

ACKNOWLEDGEMENTS

Part of this research is based on the building standards promotion project by Japanese ministry of land, infrastructure and transport.

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BIOGRAPHICAL DETAILS

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Study on Seismic Response of Escalator in Consideration of Interaction with Building During Large Earthquakes

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Keywords: escalator, analytical model, overlap allowance, seismic motion, slide friction

Abstract. In Great East Japan Earthquake in 2011, fall accidents of escalator body occurred. In the fall accidents, the escalators connected the third floor and the second floor. These occurred in commercial facilities of steel frame buildings. In general, escalators are mounted within the building structure without being fixe to the beam of the building. The cause of the fall accidents was that the escalators came off the beams of the buildings as a result of the great earthquake more than expected. After the escalator accidents, the quake resistance standard was revised in Japan. According to this standard, the layer displacement of buildings to be expected during an earthquake is more than before. However, it is considered that a non-fixed part of an escalator collides with a beam of a building by an earthquake. In addition, the collision may give compression and residual displacement to the escalator. Therefore, the purpose of this study is to grasp dynamic behavior of an escalator at an earthquake which considers impact with the beam. In this paper, behavior of an escalator during earthquakes is compared by difference of restoring force characteristics of escalators and confirm the validity of the bi-linear model. In addition, as a preliminary analysis for the vibration experiments, dynamic behavior of escalators during large earthquake is investigated by a seismic response analysis model which considers interaction with the building.

1 INTRODUCTION

An escalator is a method of vertical transportation. For example, the escalator connects a floor from another floor in buildings. In general, one side or both sides of escalators are not fixed to a beam of building in order to not deform the escalator. However, in Great East Japan Earthquake in 2011, four fall accidents of escalator bodies occurred [1]. In the fall accidents, the escalators connected the third floor and the second floor. These occurred in commercial facilities of steel frame buildings. The cause of the fall accidents was that the escalators came off from the beams of the buildings by the great earthquake more than expected. From the above-mentioned background, there is a need to clarify behavior by an escalators during an earthquake. In this paper, these elasto-plastic properties are approximated by a bi-linear model and a multi-linear model, and both models are compared. In addition, dynamic behavior of an escalator for vibration experiment is investigated by seismic response analysis which considers interaction with the building.

2 STRUCTURE OF ESCALATOR

Diagrammatical view of the escalator is shown in Fig.1. The escalator consists of steps, handrails, transport equipment parts and a truss that supports these transportation parts. As shown in equation (1), (2) and (3), the length of the overlap allowance is determined by escalator technology standard in Japan [2]. Where C is the gap between the beam of the building and the escalator, H is the height, γ is the layer deformation angle of building and 20 [mm] is margin of the overlap allowance.

$$B \geq \sum \gamma H + 20 \qquad (\sum \gamma H - C \leq 0) \tag{1}$$

$$B \geq \sum \gamma H + 20 \qquad (0 \leq \sum \gamma H - C \leq 20) \tag{2}$$

$$B \geq 2\sum \gamma H - C \qquad (20 < \sum \gamma H - C) \tag{3}$$

After the escalator accidents, the quake resistance standard was revised in Japan. According to this standard, the layer displacement of buildings to be expected during an earthquake is more than before. The layer deformation angle for design before the revision of quake resistance standard was less than 1/100 [rad]. However, after the revision of quake resistance standard was 1/40 [rad] in principle, and 1/24 [rad] or more when the structural calculation was not done. It is considered that the layer deformation of the building at the medium-scale earthquake is 1/200 to 1/120 [rad]. This value obtained by estimating five times is 1/40 to 1/24 [rad] of new standard value.

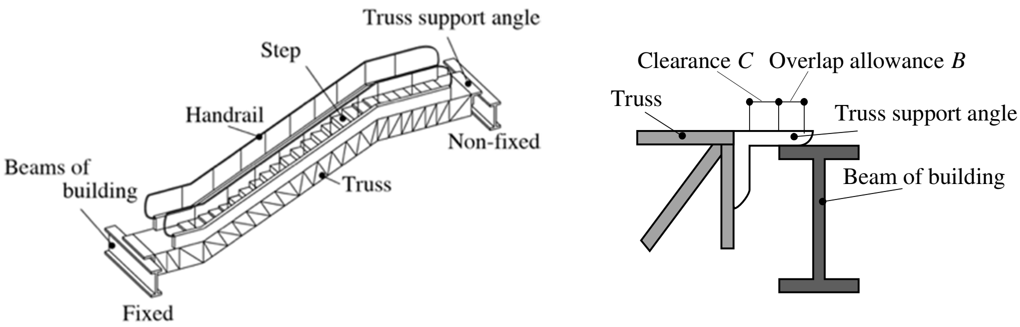


Figure 1 Escalator system and the non-fixed side of the escalator

3 ANALYTICAL MODEL

3.1 Analytical model of escalator

Target in this study is an escalator that is installed in the beam of building with fixation at the bottom side and non-fixation at the top side. This analytical model is considered that a non-fixed part of an escalator collides with a beam of a building by an earthquake [4]. In addition, this analytical model is considered that the sliding friction occurs between the beams of building and escalator. Therefore, the damping force, friction force, inertial force, and the restoring force are exerted on the escalator. As this point, it is assumed that the response of the building is not affected by the behavior of the escalator.

Figure 2 shows the analytical model of escalator. In Fig.2, m_e is the mass of escalator, F_e is the stiffness of escalator truss, c_e is the damping coefficient of escalator truss, μ_s is the static friction coefficient of escalator, μ_d is the dynamic friction coefficient of escalator, x_e is the displacement of the escalator, k_s is the stiffness of the beams of building, c_s is the damping coefficient of the beams of building, x_L is the displacement of the building on the lower floor, x_s is the displacement of the building on the upper floor. Table 1 shows parameters of escalator. The 1st stiffness k_1 of the escalator truss is calculated using results of compression experiment in past.

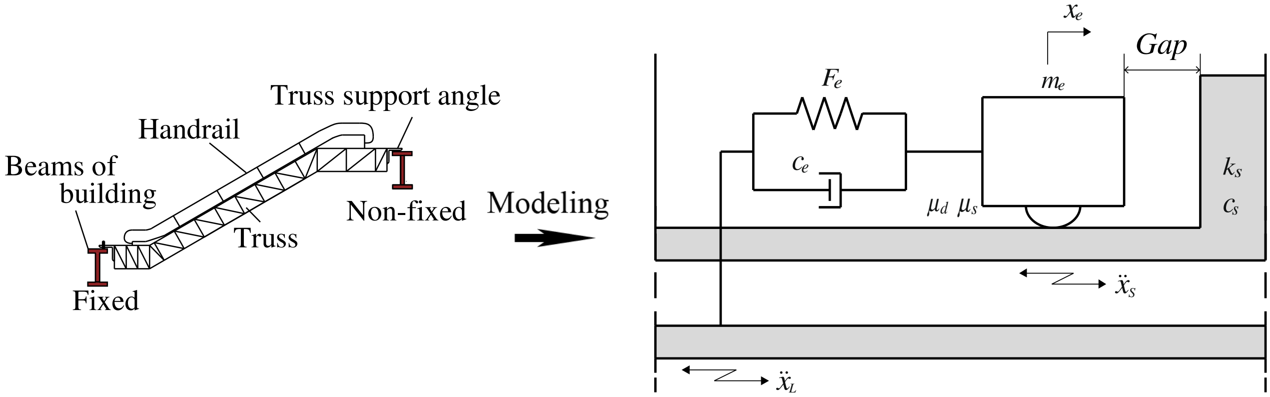


Figure 2 Analytical model of escalator

Table 1 Parameter of escalator

Mass of escalator m_e [kg]	1st stiffness k_{e1} [N/m]	2nd stiffness k_{e2} [N/m]	Yield disp. x_y [m]	Damping ratio ζ_e [%]	Friction coefficient μ_s , μ_d	Gap [m]
8000	2.75×10^7	1.10×10^5	0.02	1	0.25	0.03

3.2 Restoring force characteristics of escalator

In this study, the bi-linear model determined by the material characteristic of the escalator and the multi-linear model obtained in the compression experiments of escalators were used as the restoring force characteristics of the escalator. In the previous study, the analysis result of Truss A was shown [5]. In this study, in order to confirm the accuracy of the analysis model, the analysis result of Truss B was added. Figure 3 and 4 show a load-displacement curve. This analysis compares the result of the bi-linear model and multi-linear model.

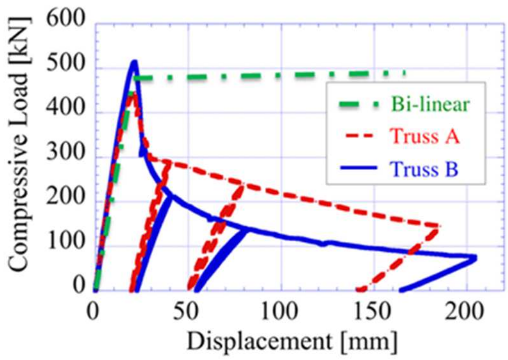


Figure 3 Load-displacement curve from experiment result and bi-linear model

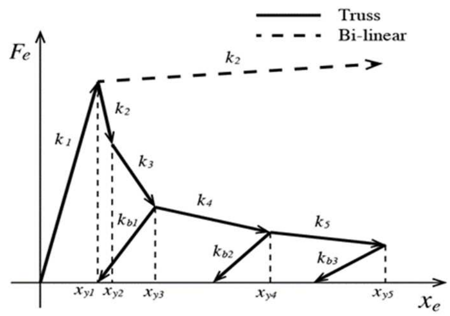


Figure 4 Load-displacement curve by linear

Table 2 Parameter of escalator truss stiffness

	Bi-linear	Truss A	Truss B
2nd Stiffness k_2 [N/m]	1.1×10^5	-2.7×10^7	-4.55×10^7
3rd Stiffness k_3 [N/m]	-	-9.7×10^6	-7.9×10^6
4th Stiffness k_4 [N/m]	-		-1.8×10^6
5th Stiffness k_5 [N/m]	-		-4.8×10^5

3.3 Equation of motion of analytical model of escalator

Equation of motion can be classified into three cases. The three equations of motion are devised, in consideration of influence by the slide friction and the collision occurred between the escalator and the building beams. Equation (4) shows the case that sliding does not occur. Equation (5) shows the case that sliding occurs. Equation (6) shows the case that collision with the building beams occurs. This equation has been shown in previous study [5].

$$\text{Case1}: \quad \ddot{x}_e = \ddot{x}_s \qquad \dot{x}_e = \dot{x}_s \qquad x_e - x_s = const \tag{4}$$

$$\text{Case2}: \quad m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) = -m_e\ddot{x}_L \tag{5}$$

$$\text{Case3}: \quad m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) + k_s\{(x_e - x_s) - Gap\} + c_s(\dot{x}_e - \dot{x}_s) = -m_e\ddot{x}_L \tag{6}$$

3.4 Analytical model of building

In this analysis, it is assumed that the escalator is installed in the three-storey steel-flame building, the response of each layer are input into the escalator analysis model. The primary natural period is 0.744 [s]. Figure 5 shows the analytical model of building. In Fig.5, m_{si} is the mass, c_{si} is the damping coefficient, k_{si} is the 1st stiffness, Q_{si1} is 1st yield load, Q_{si2} is 2nd yield load, α_{si1} is 2nd stiffness degradation rate, α_{si2} is 3rd stiffness degradation rate, $\ddot{z}_H$ is the horizontal input seismic acceleration.

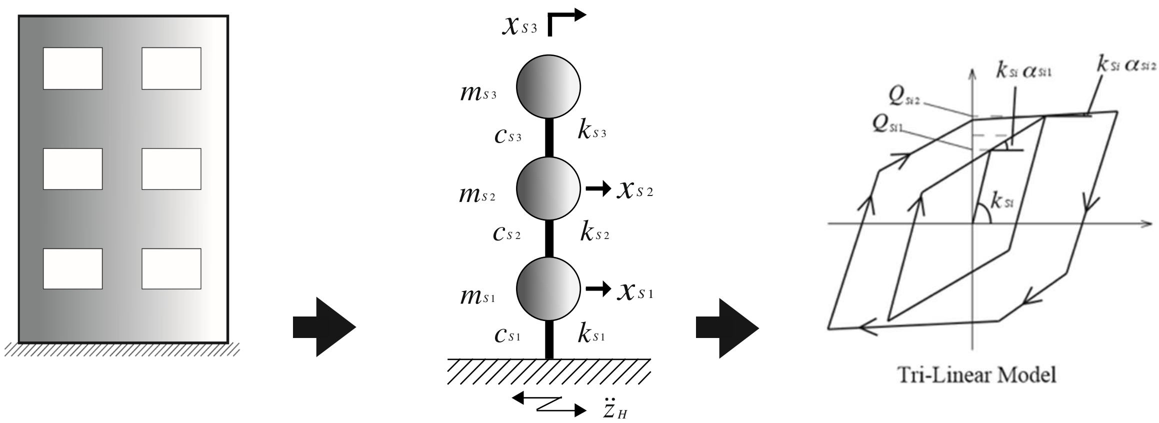


Figure 5 Analytical model of building

Table 3 Parameter of building

Layer	Mass m_s×10^6 [kg]	1st Stiffness k_{s1}×10^9 [N/m]	1st Yield Disp. x_{y1} [m]	2nd Stiffness k_{s2}×10^9 [N/m]	2nd Yield Disp. x_{y2} [m]	3rd Stiffness k_{s3}×10^9 [N/m]
3	11.21	3.48	0.012	1.25	0.047	0.623
2	9.2	3.68	0.016	1.25	0.066	0.736
1	9.7	3.83	0.019	1.38	0.075	1.23

4 SEISMIC RESPONSE ANALYSIS

4.1 Input seismic wave

Figure 6 shows the time history waveform and the response spectrum of the input seismic wave. In this paper, the K-NET Sendai NS Original wave observed at Sendai in the Great East Japan Earthquake was used. K-NET Sendai NS Original wave was obtained from Strong-motion Seismograph Network of National Research Institute for Earth Science and Disaster Prevention (K-NET), observation point is MYG013 [3]. Predominant period of K-NET Sendai NS Original wave is about 0.6~0.7 [s].

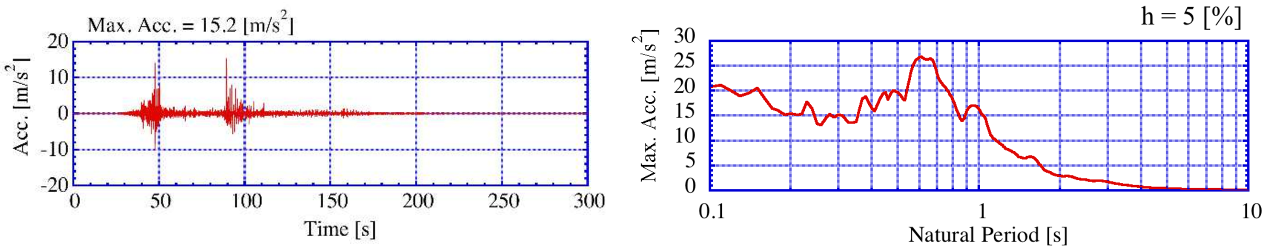


Figure 6 Time history wave and response spectrum

4.2 Results of seismic response analysis of building

Figure 7 shows result of seismic response analysis of the building. In Fig.7, the maximum acceleration of each floor, the maximum layer displacement, and the maximum layer deformation angle from the left. This building did not amplify the ground acceleration. In addition, the largest layer deformation angle was 2nd layer. From this, it is considered that there is a high risk of falls on escalator installed between 2nd and 3rd floor and above.

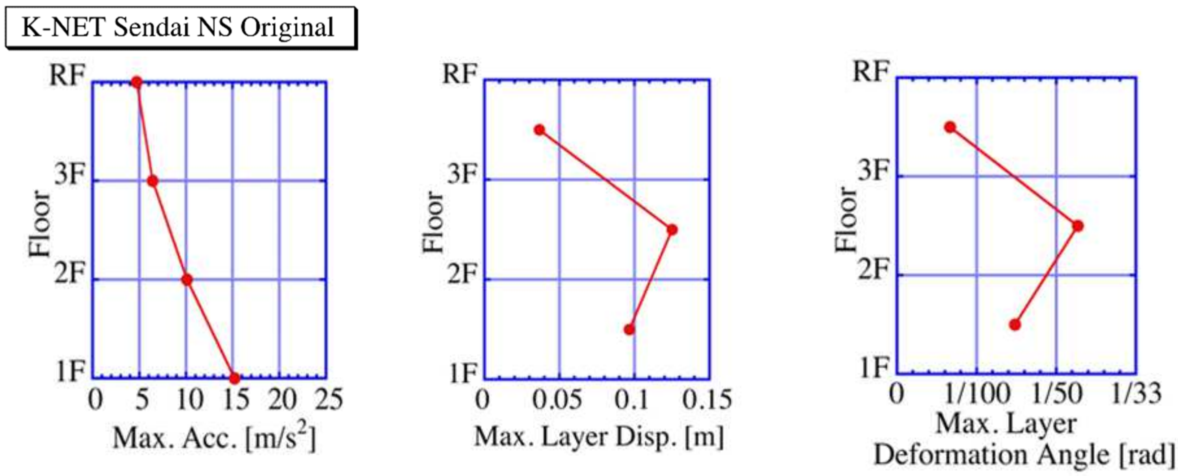


Figure 7 Response maximum values of each layer

4.3 Results of seismic response analysis of escalator

Figure 8 shows results of seismic reply analysis of escalator that is installed between 2nd and 3rd floor. When the state of escalator shifted to Case3, the response of the escalator becomes big value, because large force is generated on the escalator by collisions. As shown in restoring force of escalator, plastic deformation and residual displacement were remained. As shown in analysis results of the bi-linear model and the multi-linear model, the big difference of response was not confirmed. Therefore, influence of restoring force characteristics on the seismic behavior of the escalator is little. Figure 9 shows the maximum response values of slide displacement. In the case of the old standard, the maximum response values of the slide displacement of the escalator is higher than the value of overlap allowance, therefore the possibility of falling is high. In the case of the new standard, the maximum response values of the slide displacement of the escalator is below the value of overlap allowance, therefore the possibility of falling is low.

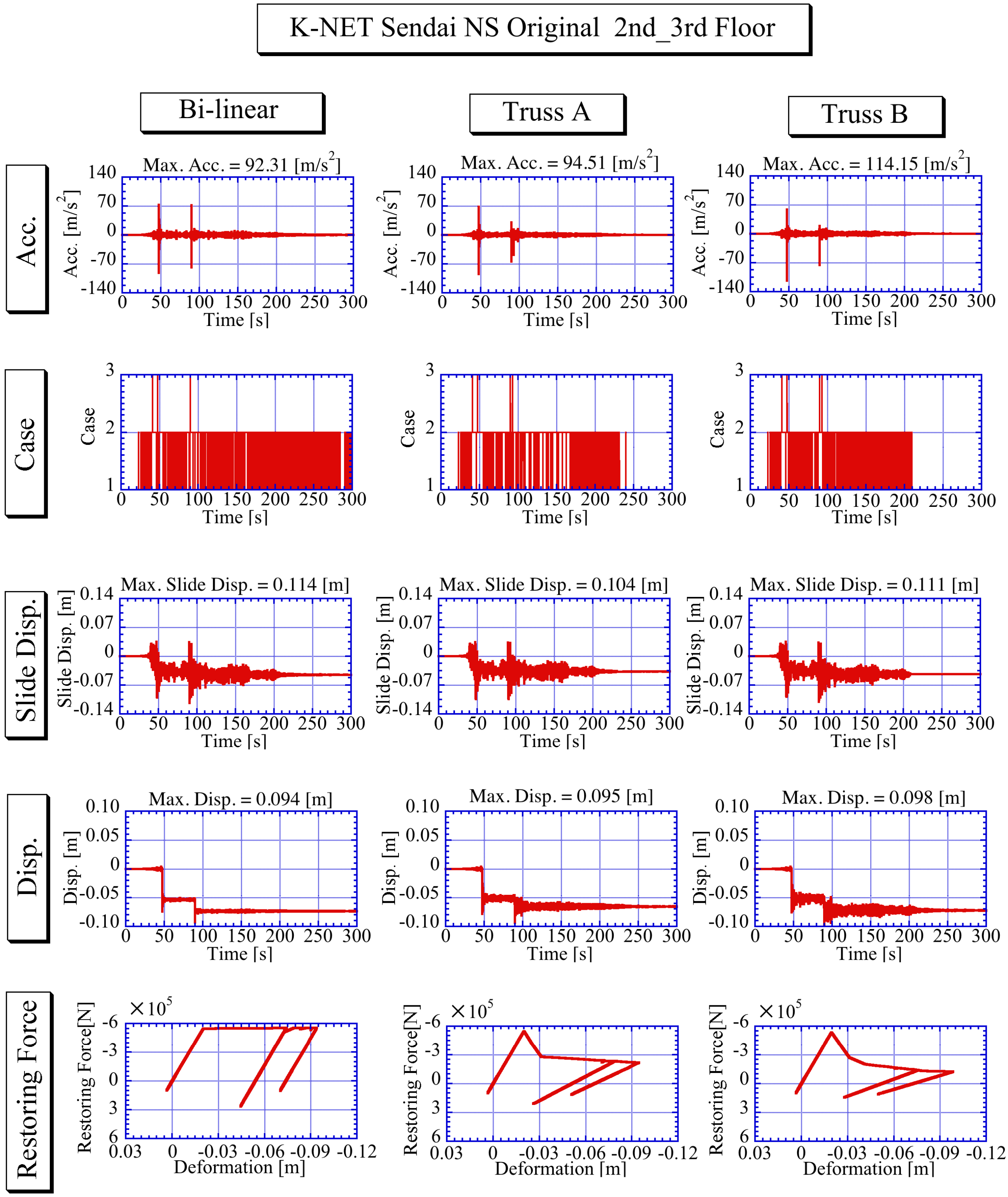


Figure 8 Earthquake reply analysis result of the escalator between 2nd and 3rd floor

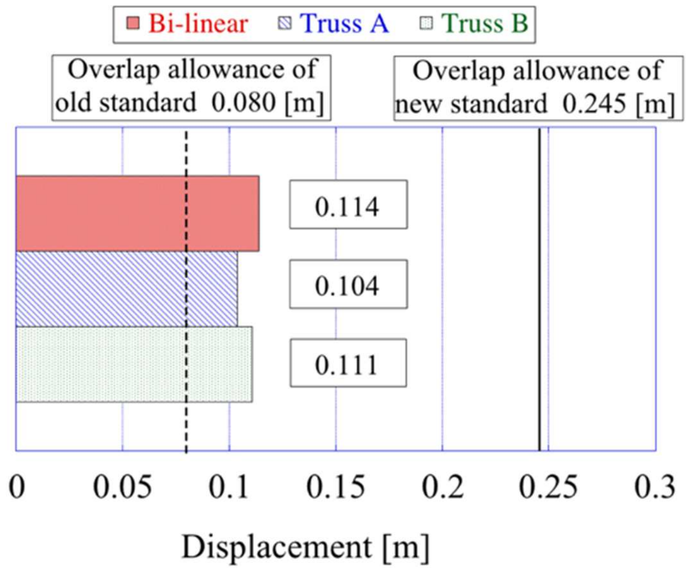


Figure 9 Maximum response values of slide displacement

5 PRELIMINARY ANALYSIS FOR VIBRATION EXPERIMENT

5.1 Vibration experiments

Vibration experiments using 0.3 scale models are planned. In this experiments, it is necessary to clarify the seismic behavior of the escalator including collision phenomenon. Figure 10 shows experimental setup used for vibration experiments. experimental setups is composed of an escalator model and buildings model. This experimental setup shakes only in the horizontal uniaxial direction.

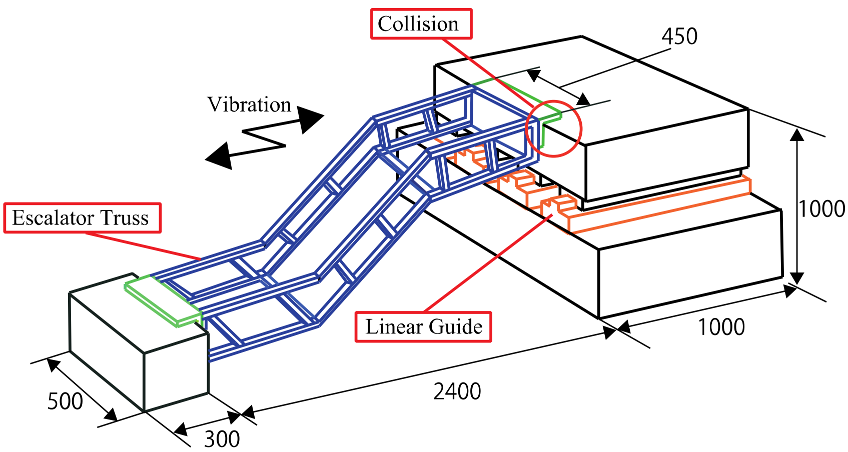


Figure 10 Schematic of experimental setup

5.2 Coupling analysis

It is the developed analysis model that can confirm the dynamic behavior of an escalator in consideration of interaction with a building. This analysis model is called a coupling analysis model. Target in this study is an escalator that is installed in the beam of building with fixation at the bottom side and non-fixation at the top side. This analytical model is considered that a non-fixed part of an escalator collides with a beam of a building by an earthquake.

5.3 Equation of motion in analytical model

Equation of motion of the escalator already indicated (Equation (4), (5), (6)). In addition, equation of motion of the building can be classified into three cases. The three equations of motion are devised, in consideration of influence by the motion of escalator. Equation (7) shows the case that sliding does not occur. Equation (8) shows the case that sliding occurs. Equation (9) shows the case that collision with the construction beams occurs.

Case1 :
$$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s - \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) = -m_s \ddot{z}_H \tag{7}$$

Case2 :
$$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s + \frac{1}{2} m_e \ddot{x}_e = -m_s \ddot{z}_H \tag{8}$$

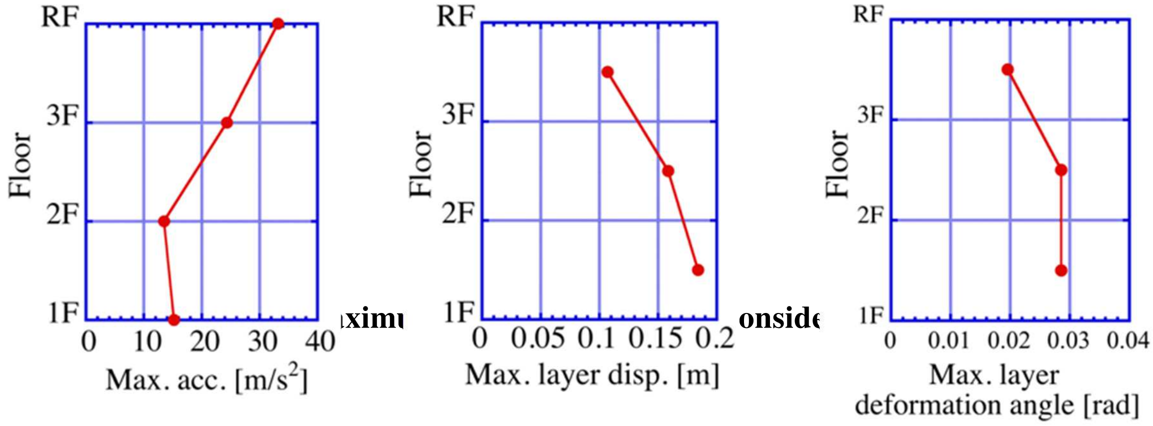
Case3 :
$$\begin{aligned} & m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s - \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) \\ & -\left[k_s\left\{(x_e - x_s) - Gap\right\} + c_s(\dot{x}_e - \dot{x}_s)\right] = -m_s \ddot{z}_H \end{aligned} \tag{9}$$

5.4 Analytical model for vibration experiments

It is assumed that the experimental setup of building used in the vibration experiment does not cause plastic deformation. Therefore, the analysis for the vibration experiment is performed assuming that the building is not plastic. Table 4 shows the parameters considering only the 1st stiffness of the three-story steel frame building. In addition, Fig.11 shows result of seismic response analysis of the building. The input seismic wave is similar to that in parameters of Fig.6.
As the result of analysis, when considering that the building is not plasticised, it can be confirmed that the response value of layer displacement is the maximum in the first layer. Therefore, the vibration experiment is performed assuming the escalator installed in the first layer of the building.

Table 4 Parameter of building considering the 1st stiffness

Layer	Mass $m_s \times 10^6$ [kg]	1st Stiffness $k_{s1} \times 10^9$ [N/m]	Natural period T_s [s]
3	11.21	3.48	0.744
2	9.2	3.68	
1	9.7	3.83	



5.5 Preliminary analysis

In this analysis model of the building, the three mass point model is simplified to one mass point. Figure 12 shows the simplification of the mass point.

Table 5 shows parameters of experimental setup that will be used in vibration experiments. These parameters are the 0.3 scale of the full scale model. Since a linear guide is passed through the friction surface between escalator model and building model, the coefficient of friction is assumed to be 0.005 (ideal value of friction coefficient of linear guide), 0.01 (the accuracy of the linear guide is bad) and 0.8 (0.3 scale of the full scale model).

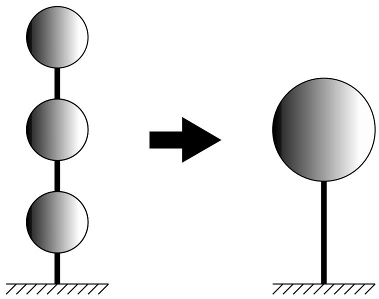


Figure 12 Simplification of the mass point

Table 5 Parameter of 0.3 scale models

Escalator				Building		
Mass	1st stiffness	2nd stiffness	Yield disp.	Mass	1st stiffness	Natural period
m_e [kg]	k_{e1} [N/m]	k_{e2} [N/m]	x_y [m]	m_s [kg]	k_{s1} [N/m]	T_s [s]
400	6.67×10^{6}	-2.40×10^{6}	0.0075	2000	1.59×10^{6}	0.223

Gap [m]	Friction coefficient
	μ_s , μ_d
0.01	0.005, 0.01, 0.8

5.6 Input seismic wave

Figure 13 shows the time history wave and the response spectrum of the input seismic wave. The input seismic wave is assumed as a wave that is used in the vibration experiment and it is scaled by the similarity law. In this paper, 0.3 scale of the K-NET Sendai NS Original 0.25 [m/s] was used.

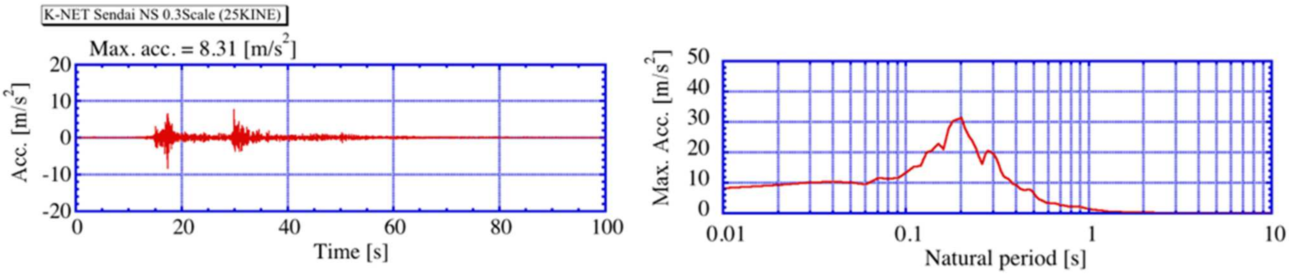


Figure 13 Time history wave and response spectrum

5.7 Results of seismic response analysis

Figure 14 shows results of seismic response analysis. In Fig.14 the numerical value (0.005, 0.01, 0.8) at the upper part of figure shows the friction coefficient. As shown in restoring force of escalator, plastic deformation and residual displacement are remained slightly. By comparing the analysis results for each friction coefficient, it can be confirmed that slide displacement and deformation of the escalator other than at the time of collision are suppressed as the friction coefficient increases. In addition, this analytical results of the building are confirmed that the behavior of building changes by friction coefficient.

Figure 15 shows the maximum response values of slide displacement. In Fig.15 the numerical value (0.005, 0.01, 0.8) at the upper part of figure shows the friction coefficient. In addition, parameters of overlap allowance are the 0.3 scale of the full scale model. In the case of the old standard, the maximum response values of the slide displacement of the escalator is higher than the value of overlap allowance, therefore the possibility of falling is high. In the case of the new standard, the maximum response values of the slide displacement of the escalator is below the value of overlap allowance, therefore the possibility of falling is low.

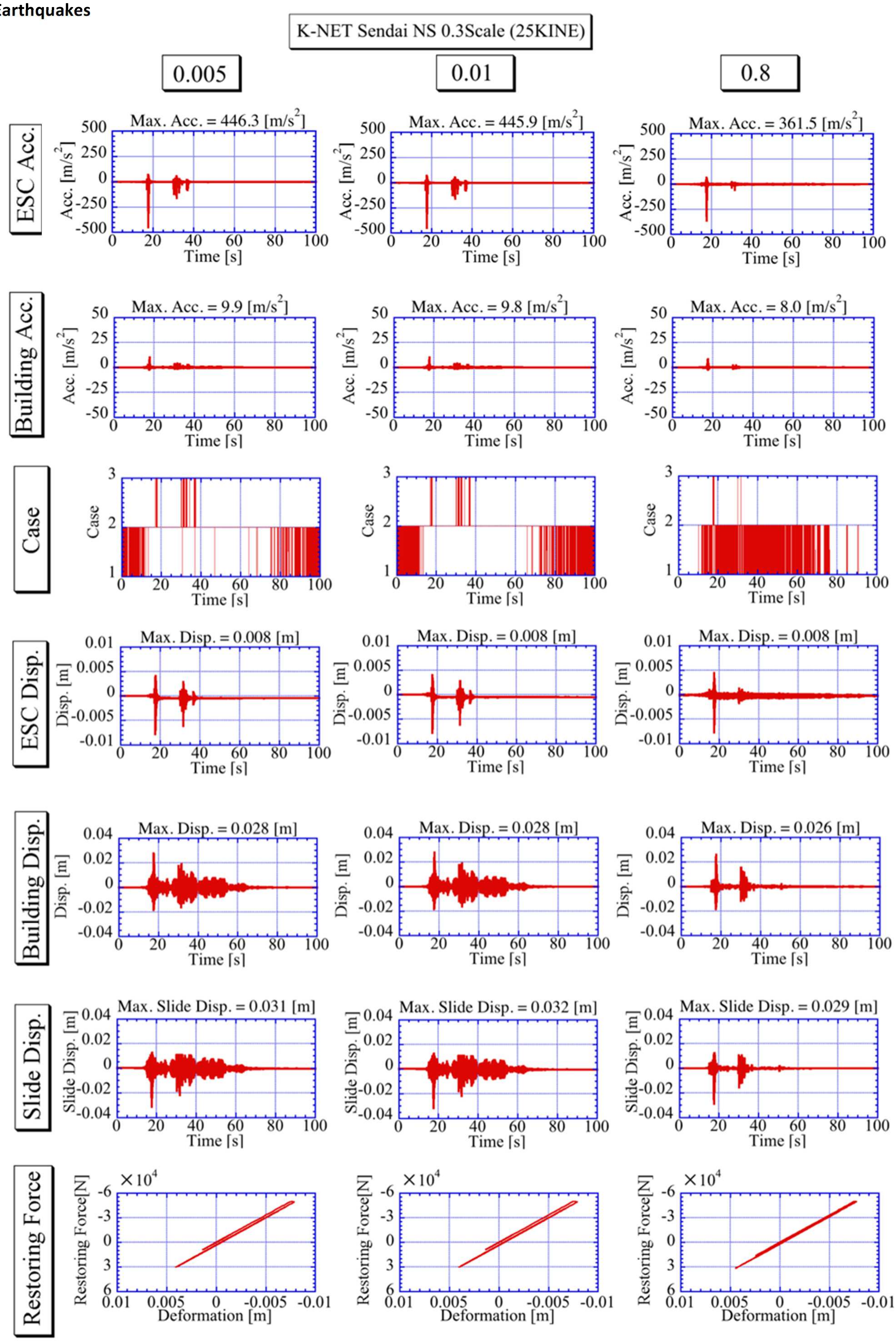


Figure 14 Seismic reply analysis result

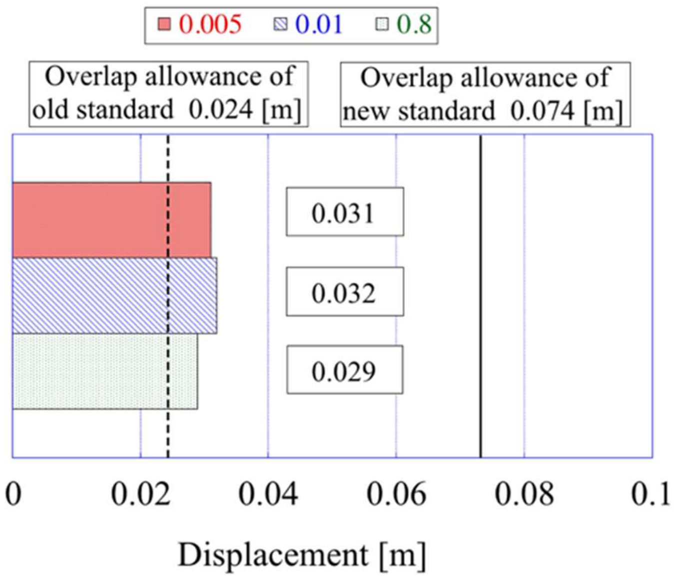


Figure 15 Maximum response values of slide displacement

6 CONCLUSION

In this study, a model of the escalator that considered the slide friction and the collision of an escalator and the building beams has been developed and analyzed. As the result of analysis, there was not the big difference with multi-linear model and the bi-liner model. Therefore, it is assumed that bi-linear model in consideration of material properties can express simply in behavior at the earthquake of the escalator. In addition, assumed the behavior of the escalator against the Great East Japan Earthquake. As the result, it was confirmed that the escalator to which the new quake resistance standard was applied was safe.

In this study, a model of the escalator that can be confirmed the dynamic behavior of an escalator in consideration of interaction with a building has been developed and analyzed. This analysis model is considered to be effective in examining the results of vibration experiments.

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BIOGRAPHICAL DETAILS

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Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MLIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MLIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Study on the Proper Performance of Lift Buffers in Revised JIS A 4306 Using Non-linear Damping Characteristic

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Keywords: lift buffer, performance requirement, non-linear damping, time response analysis

Abstract. Japanese regulatory requirement was revised in 2016. Some important safety requirements were upgraded to ensure the safety of the lift passengers. The car and counterweight buffers play an important role in a safety system. This study has been conducted for an appropriate performance of the car and counterweight buffers to satisfy the revised JIS 4306. In this paper, the analytical results using a time response analysis is shown based on the non-linear damping effect.

1 INTRODUCTION

Further safe improvement has been expected in a lift because a lot of various accidents have been occurred. Various safety devices such as an emergency stop device, a deceleration switch and an emergency stop switch have already been installed to ensure the safety of the user even in the case of a trouble into a lift. Especially, as for the probability of a falling down accident, a buffer in the bottom of lift hoistway will be a key element to prevent the progress to a serious accident.

A buffer plays a role to minimize the damage of a passenger by absorbing the shock of the falling down accident of the lift car. However, few researches have been investigated in an engineering viewpoints. In the research, it is considered that following viewpoints are important factors for the way of thinking of the safety design to the severe accidents, “Defense in Depth”, “Safety Margin and Fail safe system” and “Redundancy, Diversity and Independence”. First one is an important fundamental safety way of thinking for the design of lift to prevent the progress of a serious accident in each safety function. The other is also an important key points to keep the safety for the passengers in the lift. Although the performance requirements of a buffer has been determined in the Ministry of construction notification No.1423, an issue has occurred in an examination item, a standard for judgment, a performance requirement of buffer and so on in Japan. Therefore, as for the performance of buffer, the standard has been revised as necessary with a governor. In Japan, the performance regulation for an emergency stop device was revised in JIS A 4306 in 2016 [1].

In this study, the way of a buffer design satisfying a safety requirement of revised Japanese Industrial Standards is analytically examined. In a former paper [2], the fundamental parameters to satisfy the revised performance regulation as JIS. As the next step of the study, the way of design parameters for buffer of lift is examined in non-linear response analysis from a practical viewpoint.

2 REVISED PERFORMANCE REQUIREMENTS FOR OIL BUFFER IN JIS A 4306

2.1 Stroke

The stroke of the oil buffer is a stroke slowing down on a condition to collide at a speed of 1.15 times of the rating speed in deceleration $1g_n$, and also should be bigger than the smallest stroke calculated from the next expression.

$$L_{min} = \frac{(1.15V_R/60)^2}{2g_n} \times 10^3 = V_R^2/53.4 \qquad (1)$$

in here,

L_{min} : stroke of buffer [mm]

V_R : rating speed [m/min]

g_n (= 9.8 m/s^2) : gravity acceleration [m/s^2]

2.2 Braking performance

The oil buffer satisfy the next regulation in the performance test by 4306 JIS A 8.2.2.

- In maximum impact speed of 1.15 times of the rating speed, a weight for performance test equivalent to a maximum and minimum mass is in a free-fall, and then an average deceleration should not be exceed 1g_n when it collided with a buffer at most impact speed.
- Duration of deceleration more than 2.5g_n should not be over 0.04 seconds.

Figure 1 shows the example of slowing down characteristic of oil buffer. The average deceleration is calculated from following methods. The average deceleration is defined as the time average value of deceleration obtained from the start time of slowing down to the end time for oil buffer.

- The slowing down origin of the oil buffer is set in the time when acceleration becomes 0 m/s^2.
- The slowing down endpoint is set with the point when the deceleration becomes 0.5 m/s^2 right before the velocity 0 m/min.

$$\dot{V}_{average} = (v_1 - v_2)/(t_2 - t_1) \qquad (2)$$

in here,

$\dot{V}_{average}$: average deceleration [m/s^2]

v_1 : velocity at start point of slowing down [m/min]

v_2 : velocity at end point of slowing down (Deceleration becomes 0.5m/s^2) [m/min]

t_1 : time at start point of slowing down [s]

t_2 : time at end point of slowing down (Deceleration becomes 0.5m/s^2) [s]

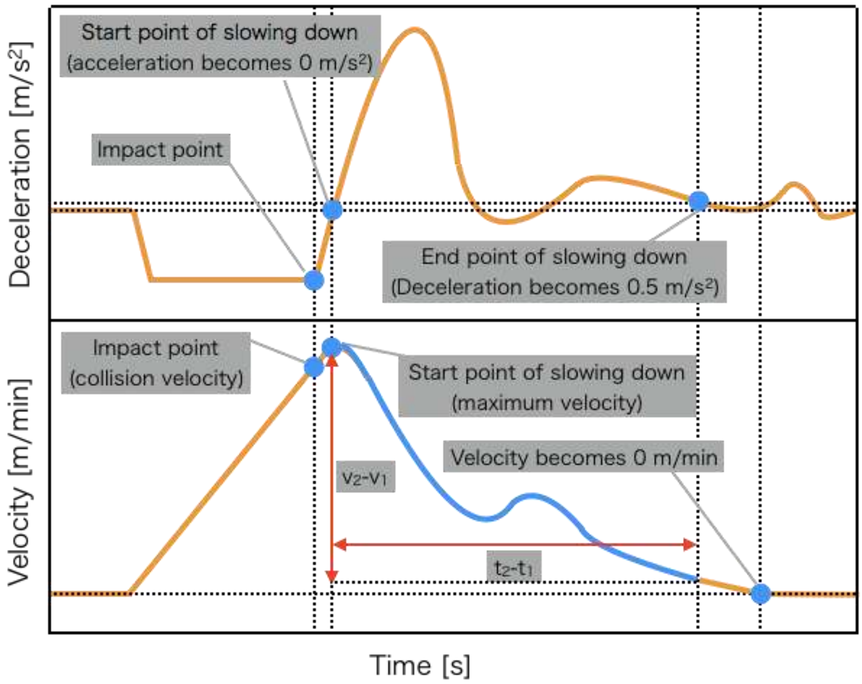


Figure 1 Example of deceleration characteristic of oil buffer

2.3 Restoring time to original position

Plunger head should be returned to an original position from the maximum sinking condition of plunger after external force was released, and also it should be less than 90 seconds.

Figure 2 shows an example of inside mechanism of oil buffer.

1) Oil buffer has a cylinder enclosing oil as an actuating fluid, and buffer action is given by fluid resistance when oil passes an orifice with the drop of the plunger.

2) Materials of a cylinder and a plunger are made by a steel.

3) Surface of the hydraulic fluid should be able to confirm.

4) The main compose of buffer material becomes an elastic materials such as a synthetic rubber.

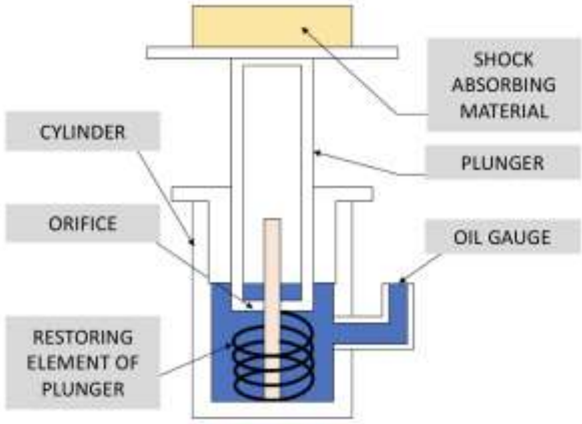


Figure 2 Example of inside mechanism of oil buffer

As for the mentioned above, although the revised JIS A 4306 has several regulations such as average deceleration, duration time of deceleration and so on, there is some example of buffer characteristic out of the design assumption.

Figure 3 shows one of example for out of design assumption. In here, a shock is absorbed instantaneously by huge deceleration in a short time, and also average deceleration is reduced in small range from a long slowdown section with low vibration reduction. Such response will occur in a combination with high capacity buffer and lightweight elevator car. Although such buffer characteristic might be able to satisfy the performance requirements, the characteristic does not play a role as a buffer.

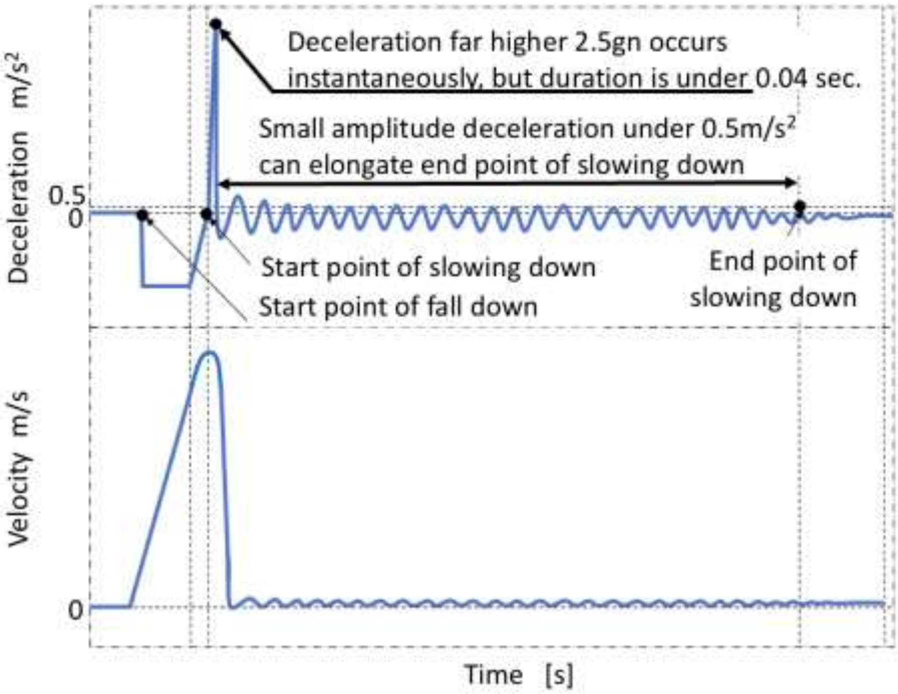


Figure 3 One of Example of Buffer Characteristic out of the Design Assumption

3 ANALYTICAL METHOD

In the previous study, the design way of oil buffer was examined to satisfy the revised standard JIS A 4306 from the relation between a natural frequency and damping ratio in 1DOF analytical model in case of linear damping characteristic. As the result, it was confirmed that the combination of design parameters are obtained and shown visually in the figures to satisfy the safety requirements.

In the next research step, the nonlinear time response analysis is conducted by using analytical model of assumed actual buffer with a nonlinear damping characteristic.

In the situation that an elevator collides with an oil buffer, one degree of freedom model that is constructed from a mass m [kg], a spring constant k [Hz] and damping coefficient c is considered to evaluate the response in sinking direction after impact between elevator car and buffer by time response analysis. Figure 2 shows a simplified diagram of nonlinear time response analysis, and also the equation of motion is as follows;

$$m\ddot{x} + c(x)\dot{x}^n + kx = 0 \tag{3}$$

here,

m : mass of car

x : relative displacement from basement of oil buffer

k : spring constant of restoring force to return a plunger head to an original position

$c(x)$: non-linear damping coefficient

Besides, the time response analysis in this time is used as non-linear damping characteristic as next expression. Besides, superscript character p means a parameter for displacement dependency on damping coefficient.

$$c(x) = \alpha x^p + \beta \tag{4}$$

The initial conditions of analytical parameters are as follows:

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

Initial velocity 103.5 m/min (=1.725 m/s): 1.15 times of the elevator of standardized speed 90 m/min

The spring constant is set to k = 300 N/m, because the plunger head returns to initial position by spring element.

In this paper, the analytical results is summarized about a non-linear damping characteristic to satisfy the revised JIS A 4306 from the evaluation factor such as average deceleration, maximum displacement and duration time in constant deceleration.

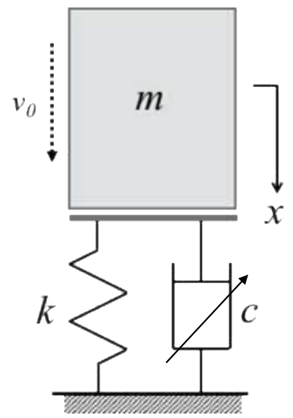


Figure 4 Analytical model for time response analysis of design way for elevator buffer

4 ANALYTICAL RESULT

Before the non-linear time response analysis, the analytical parameters of non-linear damping characteristics are examined in condition with $\alpha = 0$ or $\beta = 0$. Besides, the analytical parameter p is 0 in here because the fundamental qualitative tendency is examined at first. Equation of motion (4) is solved by using Runge-Kutta Gill method for a non-linear time response.

Figure 5 shows the relation between sinking displacement of buffer and maximum damping force in the case of $\beta = 0$ and $1.0\times10^5 \leq \alpha \leq 9.0\times10^5$. It is confirmed that the maximum displacement decreases and the maximum force increases by increasing α. Next, Fig.6 shows the relation between maximum displacement and maximum damping force in the case of β is the parameters. It is confirmed that the displacement decreases and the maximum force increases by increasing β as the same tendency in case of α. As the results, the time response analysis is carried out using α as a parameter for a non-linear damping effect, because an initial damping coefficient makes to increase a response acceleration and also to be undesirable as an actual buffer.

Figure 7 shows the time response in displacement, velocity and acceleration after a car impact to a buffer as the analytical parameter α. It is confirmed that the response displacement and duration time of slowdown decreases in increasing α as shown in the figure. On the other hand, increasing α leads a large maximum acceleration and a reduction of response duration.

Finally, it is examined that the range of parameter α satisfy the regulatory requirement. Figure 8 shows the relation between the responses and analytical parameter α. In the condition that the analytical parameter α is over 7.2×10^5, the average deceleration exceeds $1g_n$ which is a regulatory requirement in the revised JIS 4306. Moreover, in the case of range of α over about 3.0×10^5, the maximum stroke does not satisfy the safety requirement. Therefore, next range of the parameter α shows the specification condition of buffer in the case of satisfying the safety requirement and the non-linear damping characteristic possibility.

$$2.0\times10^4 \leq \alpha \leq 3.0\times10^5$$

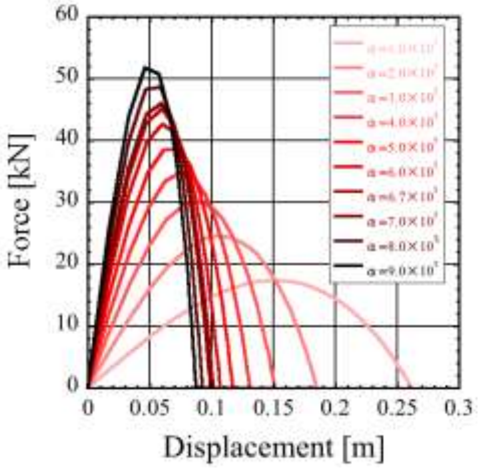
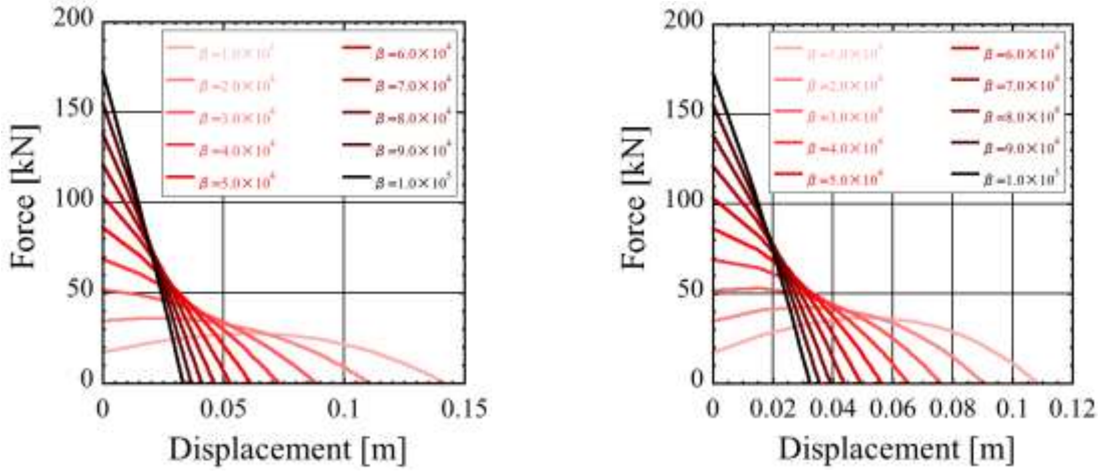
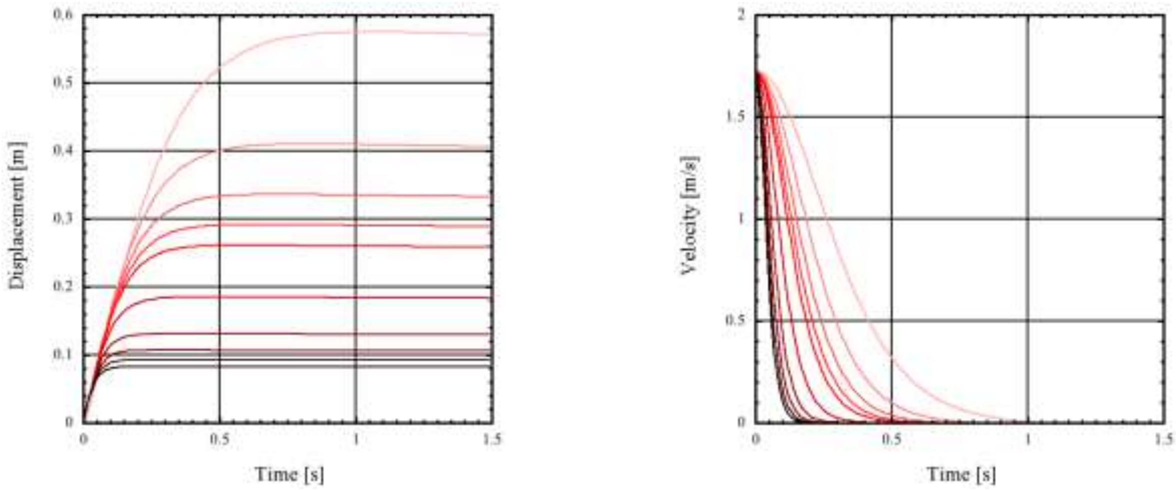


Figure 5 Relation between displacement and force in $\beta = 0$ *and* $1.0\times10^5 \leq \alpha \leq 9.0\times10^5$

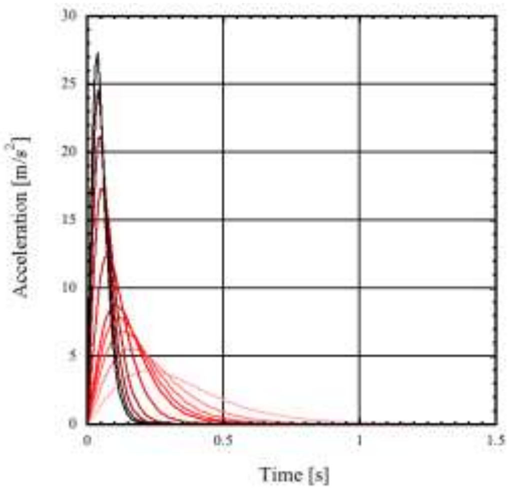


(a) $\alpha = 2.0\times10^5$ **(b) $\alpha = 4.0\times10^5$**

Figure 6 Relation between displacement and force in $1.0\times10^4 \leq \beta \leq 1.0\times10^5$

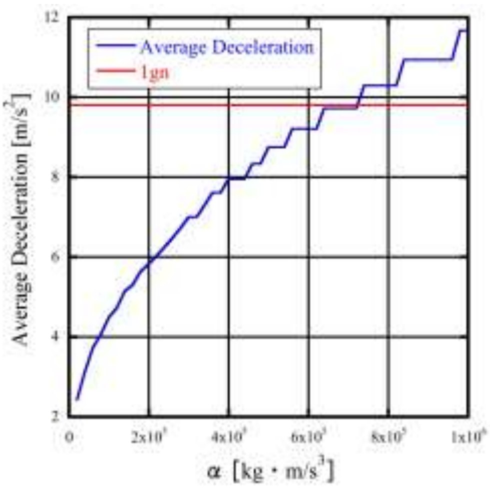


(a) Response displacement **(b) Response velocity**

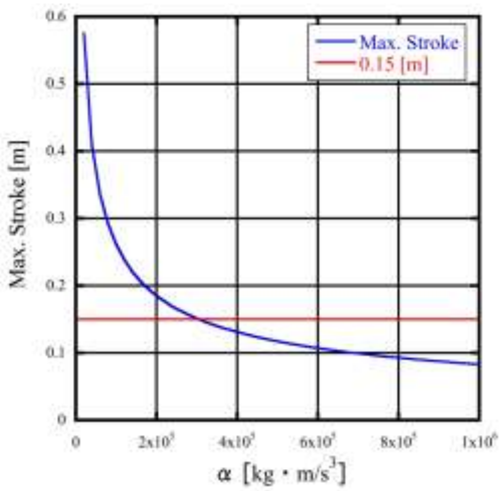


(c) Response acceleration

Figure 7 Response displacement, velocity and acceleration as the analytical parameter α



(a) Average deceleration



(b) Maximum stroke

Figure 8 Relation with responses to satisfy the regulations as the analytical parameter α

5 CONCLUSION

This study have carried out about the suitable design way of elevator buffer to satisfy the revised industrial standard JIS A 4306 from the time response analysis using an analytical model of non-linear damping characteristic in 1degree freedom (1DOF) model. In this paper, as the result, it was confirmed that the analytical parameters α was obtained to satisfy the performance requirements from the non-linear time response analysis using analytical model of a nonlinear characteristic. In the next step, the analysis will be conducted to investigate an actual condition by considering an effect of gravity in a car and a buffer, and also the car load will be changed to satisfy several load conditions. Because the response analysis carried out since the starting point in the condition that the weight of mass balanced to restoring force in spring element of dynamic analytical model.

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The Effectiveness of Remote Lift Monitoring with Regards to Lift Reliability

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Keywords: lift, remote monitoring, elevator, maintenance

Abstract. A study was carried out to understand more about whether the lift industry can benefit from the internet of things (IoT); specifically, to understand whether connecting lifts electronically to the internet and then remotely monitoring various elements of the lift can reduce breakdowns, by enabling the service company to identify a maintenance programme that ensures better reliability. Ten lifts were selected that were alike in type, usage and condition to compare similar lifts and rule out any anomalies associated with this. The selected lifts were then fitted with a remote monitoring device (RMD) that connected directly to the lift control panel. Failure mode, effects and criticality analysis (FMECA) was the method used to quantify numerically the effects of lift breakdowns. The lifts were retrospectively analysed 160 days before a remote monitoring system was fitted and 160 days after. With the remote monitoring device fitted, supervisory engineers could influence engineers' decisions, and to interact with the client. The results were averaged over the 3 sets of data to give an average score. Overall there was a 63% reduction in the number of calls. The data showed that remote monitoring can offer many advantages to managing a lift system in terms of maintenance and reliability, specifically task-based maintenance.

1 INTRODUCTION

The subject of this paper was inspired by what the author perceived as the downward spiral in maintenance standards, due to reduced costs and maintenance frequency. It was felt that this reduction in maintenance frequency, has in turn led to a reduction in reliability, with an increased level of breakdowns and downtime.

A lift breakdown is a failure and a failure can be most often described as a shortfall between performance and standards [1]. There can be several reasons for failure, from misuse; in its various guises, wear and tear related factors, through to component failure which could be a result of poor maintenance or poor initial design. The duty or wear and tear issues may be considered a failure of maintenance, if sufficient action is not taken to ensure timely repair or replacement is not undertaken.

Lift reliability is an ongoing issue for the industry. Whilst comparable industries, for example, the motor trade have seen significant drops in the average number of breakdowns per annum over the last few decades, the lift industries' breakdown rate is thought to be some 3-5 breakdowns per year (Mitsubishi, 2016). There is a possibility that the breakdown rate was higher in the past, as for example, there has been technological advances with sealed for life bearings and more reliable control systems widely in use, together with a reduction in mechanical hardware, an expected fall in the number of breakdowns should be expected.

However, the lift industry has evolved over recent years and has taken advantage of the developing technologies as they have progressed. The control panel, for example, by using microprocessor based technology to replace previous relay logic, has in turn eliminated many of the failures previously encountered, with relay logic controllers, such as contact wear and contact failure along with dry solder joints found through interconnections. It is becoming more common to see in the lift industry the CANbus system being used, which reduces the amount of wiring and interconnections between component parts, therefore improving overall reliability within the control system.

So as far as the advances in technology are concerned the lift industry has also made considerable progress. So, the question is, why are lifts still breaking down on average 3-5 times a year? Part of the explanation for this, could be that much of the lift equipment in question is not the new equipment mentioned above and could instead be 30 or more years old, and along with a ‘one size fits all’ approach to maintenance, then the appropriate level of maintenance is not always given. This is exacerbated by a price war, where there’s a ‘drive to the bottom’ currently being experienced and the only way profits often can be maintained is by cutting the number of visits, or the labour used to service the lifts.

The above are somewhat interconnected in that the old stock when originally designed, for 12 monthly visits a year, was largely because the oils and the grease required topping up. If we were to take a 50-year-old Express-Evans lift, it had grease filled cartridges that required winding in monthly and the guides needed oiling every month. The contacts may have needed cleaning due to arcing, carbons and braids required replacing, air gaps needed adjusting, etc. The newer lifts require less maintenance; sealed bearings have negated the need for greasing points, electronics and “sealed” relays and contactors have negated the need to file carbons and contacts.

It is observed that the client may seek a less expensive alternative to their present incumbent, because “we never have any problems with our elevators” so why do we pay so much [5]. So, they have paid a proactive maintenance company giving good preventive maintenance, only for the discerning lift company to be penalised by their own success. Indeed, it may even be found that by switching to a less expensive maintenance regime, for example less visits per annum, or a basic contract that involved only lubrication, and minor adjustments, that the building owner will not see a discernible difference in the first weeks or months, due to the previous regime, but it’s inevitable that less maintenance will result in more wear and potentially more breakdowns.

Further, it can be found that the clients with larger portfolios will often have a mix of lifts, with varying levels of maintenance needs. These variations can be due to different ages, types: for example, traction, hydraulic or chain driven, or usage rates may vary widely. The inclination can be, to look for a “one size fits all” solution. This is often driven by the need to introduce a level playing field for competing lift companies, which will in turn produce competitive comparable quotes. Whereas this will almost certainly successfully produce a range of quotes, enabling the client to choose the lowest, it will not necessarily produce the most effective maintenance regime for the lifts on offer. The drive for the cheapest price often results in 4 service visits a year, which may be suitable for new lifts but completely unsuitable for the older or heavily used type.

1.1 Maintenance Regimes

There are a variety of types of maintenance on offer from a range of service providers, and from they would normally fall under three general categories [2]:

1. **Oil and grease**, where the maintenance company will provide an operative to maintain lubrication levels, ensure that the pit, shaft, motor-room and car top are free from dirt and debris, and make any minor adjustments. All other attendances, such as breakdowns and parts are chargeable.
2. **Fully comprehensive**, as the oil and grease, but with the addition of providing breakdown cover that is included in the price.
3. **Premium comprehensive**, that would provide additional services such as condition monitoring, remote monitoring, and performance guarantees, where there is a penalty charged if the lift were to fail more than a pre-agreed number of times in a period.

A brief history of maintenance within the lift industry was given by Rory Smith at the 2016 Lift Symposium [4].

- **Reactive maintenance** - the initial task of the maintenance or service engineer was reactive, that is they would attend the site and repair the lift in the event of a failure and return the lift into service.
- **Preventive maintenance** - was the next logical step forward to reduce the number of breakdowns, for example by ensuring that the lubrication regime was maintained, and appropriate adjustments were made to the machinery, then the goal was to prevent the lift from breaking down, and to increase the overall service life of the lift.
- **Usage based maintenance -** evolved from the late 1990's, with the principle purpose to adjust the quantity and timing of maintenance visits so they were based on the number of journeys made, in much the same way as the number of miles driven in a car, where the oil is changed, or the number of miles driven before the cam belt is routinely changed, therefore the data is of use to the incumbent to enable a more bespoke maintenance regime.
- **Condition based maintenance –** Although this type of maintenance has been the cornerstone of efficient maintenance of technical equipment [3] in many industries for some years, it has been comparatively late coming to the lift industry. The concept of measurement and analytics of physical properties, and measuring magnitudes gives an objective view of the potential condition of the components under surveillance.
- **Task based maintenance** - the production of maintenance task lists based on the condition or the use of the lift.
- **Data driven maintenance** – is to combine all the maintenance regimes into one system.

1.2 Empirical Study

An empirical study was carried out to establish whether remote monitoring can affect the reliability of a lift. The aims of the study were:

1. To investigate the effective use of the data gained during remote monitoring of the lift.

2. To establish the effectiveness of a remote lift monitoring system on its reliability.

The group of lifts monitored, were a similar age, condition and type. That is, low rise, goods lifts with manually operated doors. The lifts were operated by the same retailer, although the usage varied. All lifts had been refurbished in the last 5 years and had the same modern microprocessor based lift control system, and encoder based signalling systems. The lifts were a combination of traction and hydraulic.

The aim of the study was to understand more about whether the lift industry can benefit from the internet of things (IoT); specifically, to understand whether connecting lifts electronically to the internet and then remotely monitoring various elements of the lift can reduce breakdowns, by enabling the service company to identify a maintenance programme that ensures better reliability.

2 METHODOLOGY

The lifts were fitted with a device (RMD) that monitors the lift through the control panel. The control panel is a purpose designed system using a PIC based microcontroller to undertake the lift functions such as call processing, initiating motor control, (via a VVVF drive) stopping and levelling (via an encoder) and connects to the RMD serially via RS485.

Once appropriate data was received from the individual lifts, the data was acted on in the most appropriate way to reduce the frequency of breakdowns. By considering the reasons behind each failure then various techniques could be employed to prevent the same events from occurring again.

Various parameters were monitored including: -

- number of journeys,

- start failures,
- gate lock failure,
- car gate faults.
- gate locks tipped in both high speed and low speed,
- stuck pushes.
- out of door zone.
- number of door operations.
- lift position.

The method used for analysing the reasons for failure in more detail, was Failure, Modes, Effects and Critical Analysis (FMECA) [6]. FMECA includes a critical analysis, which is used to chart the probability of failure modes against the severity of their consequences. This enables the user to highlight the resulting failure modes with relatively high probability and severity of consequences. This further allows remedial effort to be directed where it will produce the greatest value. The FMECA process enabled a number to be put on the effect to customers of lift failures. These numbers were then compared using the same techniques before and after the remote monitoring system has been fitted to the lift. Therefore, if there is a reduction in the numbers it could be expressed in a meaningful number or percentage.

2.1 Recording Breakdowns

The methodology was to use the data from the RMDs from the sites previously identified (10 stores identified by geographical location: Bow, New Addington, East Acton, Formby, Kirkby, Newport Commercial, Eltham, Altrincham, Gloucester, Watford and Greenford), and evaluate whether reliability has improved, the time scale is 160 days before RMD was fitted and 160 days after RMD was fitted. The customer has its own system of recording reported faults named Compass. This is a central system that the stores use to communicate with their head office to record any maintenance issues, request subcontractor such as the lift provider attendance, monitor reactive and preventative maintenance visits and to log quotes and invoicing. The subcontractor's attending engineer will record their actions onto the Compass system once completed. This system is live and access to the data was readily available for analysis. Therefore, independent data from the Compass system was viewed for 160 days prior to RMD and then 160 days after and then examined to see if breakdowns have reduced in the second 160-day period.

Action was taken when a fault or breakdown occurred and if the breakdown was to reoccur then resources were used, for example: technician level involvement to quickly resolve the issue. This, in the first instance, was remotely administered.

2.2 Recording Usage and Adapting Maintenance Regime to Suit Usage

The lift usage varied between sites, and usage was measured from the busiest stores at approximately 100,000 journeys per year. It was found that these lifts often ran out of guide lubricant and were often reported as noisy, resulting in additional visits. Given that many of these lifts were more than 50 years old and required grease pot rotation and regular lubrication. The service regime was traditionally set at monthly intervals. It was therefore prudent to establish a regime such that if the lift experienced more than 10,000 trips per month then additional service visits will be implemented, i.e. after every 10,000 trips, and an alert set to inform the engineer supervisor.

A systematic record made by the RMD was regularly inspected to see if any events were frequently occurring, that may eventually impact on reliability. The following events were thought to be significant:

- Start failure
- Slow speed gate lock trip
- High speed gate lock trip
- System reset
- Stopped out of door zone
- Gate lock fault

3 DATA ANALYSIS

The retail stores observed within this study were averaging some 6 faults per lift per store over the range of 470 lifts in total.

With reference to Fig 1, the 10 sites are identified by their geographical location, and referred to this on the x-axis of the charts below. The blue columns represent the actual number of faults logged for all the sites with RMD installed during 2016. Only 7 sites had 6 months data prior to RMD installation, and 6 months data after RMD installation. For example, Bow had an RMD installed on 29th February 2016, so the calls 6 months prior to the installation were 31 (blue).

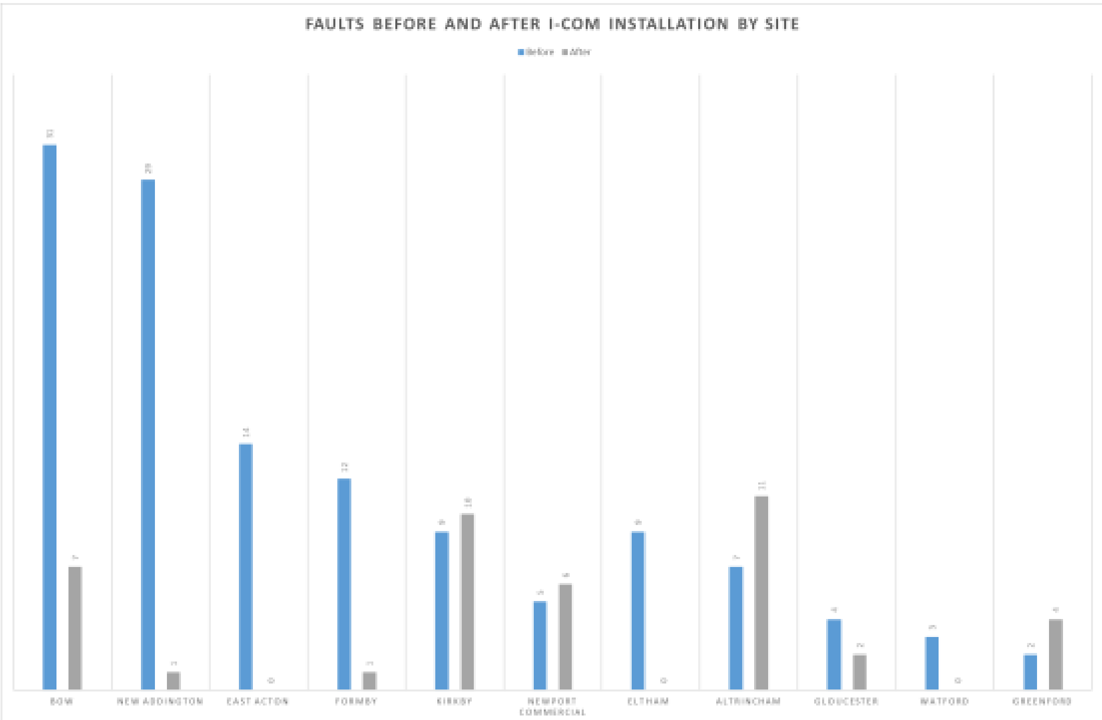

Figure 1 Faults Before and After RMD Installation by Site

Overall there was a 63% reduction in the number of calls. Where there was a high number of annual journeys undertaken by any of the lifts, the maintenance regime was increased to every 8000-10,000 journeys, in some cases effectively doubling the maintenance visits. The maintenance was also more targeted focussing more on the issues registered on RMD. There was more interaction with the staff as engineers were alerted to remotely (email) of faults, resulting in the staff understanding the co-relation between how they use the lift and the frequency of breakdowns.

Generally, faults other than housekeeping reduced. The housekeeping faults increased due to more detection from RMD, this was generally generated from the “start failures”. Several start failures were expected as the operators did not always close the doors properly. It was deemed that anything more than 10 failures daily would prompt a phone call to the store, or if persistently requiring a visit from the engineer. The visit may have entailed instructing staff, to keep the tracks clear, or minor adjustment to the lock mechanism. The ROA were also significantly reduced, in effect there should not have been any ROAs as it can be seen if the lift is in service prior to dispatching an engineer, however, the communication between the team monitoring the lifts and the operations teams taking the breakdown calls was not always 100% resulting in engineers being dispatched.

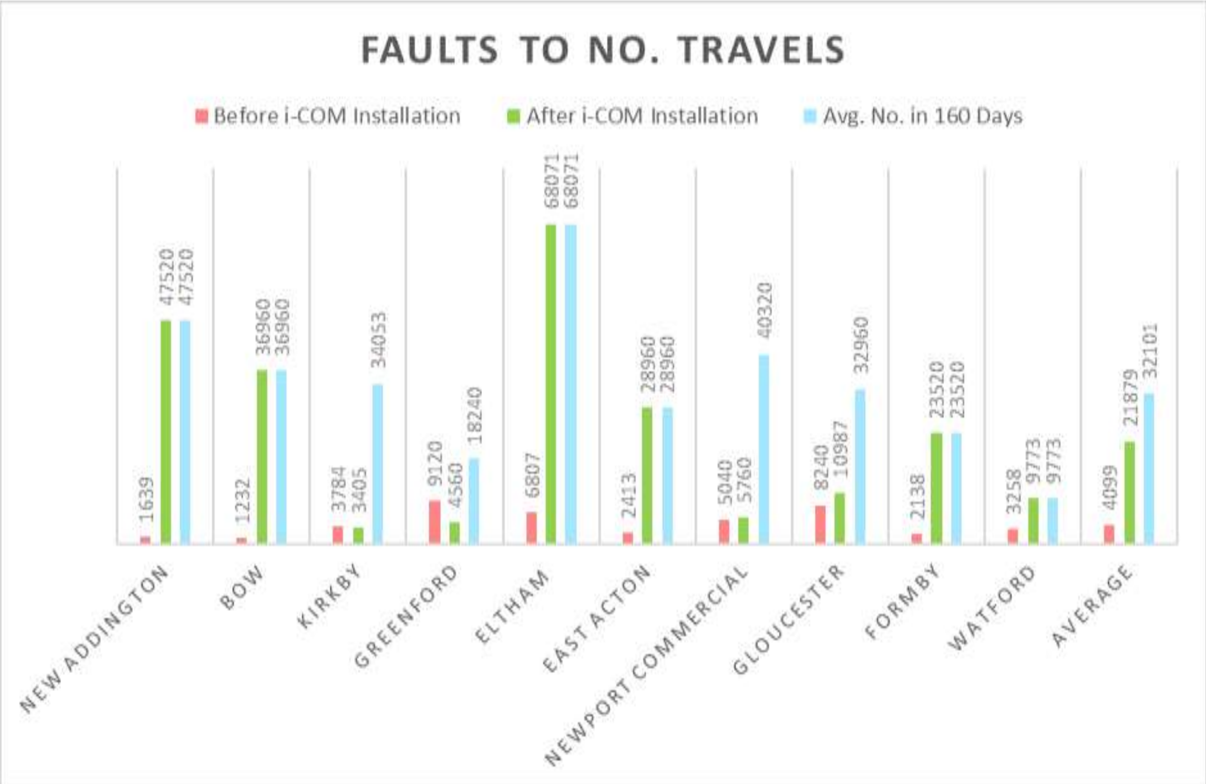

Figure 2 Graph to Show Number of Faults to Journeys

4 CONCLUSION

The data clearly shows that remote monitoring of lift installations will facilitate more effective observations, a faster route to fault detection and better maintenance scheduling of the lift by enabling more observations to take place more frequently. This is due to the observational element being transformed to a desktop exercise. The number of journeys per fault also increased, along with a reduction in breakdowns. There are several explanations for the results, including:

- Better and more targeted maintenance
- Faster fault identification
- Faster fault resolution.
- Eliminating false reporting of breakdowns
- Improved communication with lift user (educating correct lift usage).

Since the end of the study, the development of the RMD and lift maintenance regimes associated with this has continued and with the

- FMECA system automated and used to generate a score,
- If the score was over a pre-set number (100) the issues well examined by a technician and a task list compiled to remedy the issues
- The task list was undertaken by a field service engineer
- The FMECA was observed, and if it was reducing in the coming days then the result of the task list was positive
- If it continued then the engineer was ordered to return to site to carry out the tasks a second time, or a supervisor was ordered to attend alongside the engineer
- The reduction in breakdowns has continued at a similar rate
- Concludes that RM will help to ensure appropriate levels of maintenance is carried out.
- RM combined with task driven maintenance will help identify areas where maintenance should be carried out.

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BIOGRAPHICAL DETAILS

Charles Salter is the owner and Managing Director of ACE Lifts. He has an MSc in Lift Engineering and has been in the lift industry for around 40 years.

The Evolution of Lift Traffic Design from Human to Expert System

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Keywords: traffic design, expert system, lift, elevator

Abstract. The (human) lift traffic expert solves a number of equations (a mathematical model) to select a suitable lift installation to meet certain design criteria. The expert often then has to adjudicate between several possible designs. This requires a great deal of experience and perspicacity. Many lay people (architects, developers, facility managers, general M&E consultants) and also some lift industry personnel (sales engineers, support staff) desire a simple and quick method of selection.

Over the years there have been many attempts to provide look up tables and charts for a quick selection. This paper describes these historical attempts from the 1960s onwards to the present time. The mathematical models are explained and the design process is described. A demonstration of the design process using a simple spreadsheet presented illustrates the expert decision-making process. The creation of a non-human expert system is discussed in [20].

1 INTRODUCTION

This paper looks at the lift traffic design process applying calculations that a human carries out and whether it can be built into an expert system.

The calculation method uses a mathematical model for uppeak (incoming) traffic and a collective control system to design and evaluate the characteristics of a lift installation. If applied correctly, it determines a lift installation in terms of rated load, rated speed, number of lifts, etc., that generally also meets the requirements of other traffic conditions, such as midday, down peak and interfloor traffic [1]. Furthermore, the calculation method is verifiable, repeatable and reproducible.

The calculation method is based on pure uppeak traffic and uses the classical uppeak analysis equations to determine the two defining design criteria: (1) the lift system handling capacity and (2) the interval. These values can be used to evaluate a lift installation's ability to meet the Quantity of Service requirement, which is represented by (1) and Quality of Service requirement, which is represented by (2).

In the period from 1965 to 1990 lift traffic designers decided on a value for the required uppeak interval, determined a lift installation that satisfied that value and then calculated the uppeak handling capacity. If the handling capacity was equal or greater than the required value the lift installation was defined.

From ca1990 the requirements were reversed and the lift designer decided on a value for uppeak handing capacity, determined a lift installation that satisfied that value and then calculated the uppeak interval. If the interval was equal or less than the required value the lift installation was defined. This was the first major evolution.

Having carried out a calculation the lift designer might then simulate the chosen lift installation and check parameters such as passenger average waiting times, car loadings, queue lengths, etc.

2 CALCULATION METHOD

The equation that had to be solved to ensure the lift installation could transport the number of passengers arriving in five minutes was and still is:

$$HC5 = \%POP \tag{1}$$

where:

%POP is the passenger demand in persons arriving in five minutes.

HC5 is the lift installation five minute (300 second) uppeak handling capacity in persons per five minutes

The lift traffic designer needs to determine a lift installation that provides a *HC*5 that is equal or larger than *%POP*. Thus, to solve Equation (1) a value for *HC5* needs to be calculated for the proposed lift installation.

*HC*5 can be calculated for a single lift from the equation:

$$HC5 = \frac{300 \times P}{RTT} \tag{2}$$

or for a group of *L* lifts from

$$HC5 = \frac{300 \times P \times L}{RTT} \tag{3}$$

where:

P is the average number of passengers in the car at departure from the main entrance floor.

RTT is the round trip time, in seconds (s), of a single lift during uppeak traffic.

The value of *RTT* can be calculated from the Equation (4):

$$RTT = 2Ht_v + (S+1)t_s + 2Pt_p \tag{4}$$

Giving:

$$HC5 = \frac{300 \times P \times L}{(2Ht_v + (S+1)t_s + 2Pt_p)} \tag{5}$$

where:
H is the average highest reversal floor
t_v is the rated speed of the lift (m/s)
S is the probable number of stops

t_s is the time consumed in stopping (s)

P is the average number of passengers in the car
t_p is the average passenger transfer time (s)

It will be noticed that the parameter *P* appears both in the numerator and the denominator of equation (5). This is called a two-point boundary problem. It is solved by the lift designer altering the value of *P* until Equation (1) is satisfied.

NOTE: The second design requirement (2), the uppeak interval is given by:

$$INT = \frac{RTT}{L} \tag{6}$$

where:
INT is average time, in seconds, between successive car arrivals (or departures) at the main terminal (or other defined) floor

The number of lifts is the prime parameter to meet the second design requirement.

The full elaboration of the mathematics is given in [2]. The following history chronicles a search for a simple process, which hides the mathematics.

3 HISTORY

3.1 1890-1960 Many workers

Lee Gray in his paper [3] presented at the 2017 Lift and Escalator Symposium covered lift traffic analysis up to 1960. It reveals a number of attempts to provide formulae and charts to select a lift installation. These attempts were not taken up by the lift industry and were only known to a very small number of people.

3.2 1967 - Strakosch method

A step change occurred when George Strakosch published *Vertical transportation: Elevators and Escalators* in 1967 [4]. He provides a manual method to carry out a traffic design, see Table 3. He also utilises a table of probable stops, see Table 1 and a table of lift car occupancy, see Table 2. It is to be noted that all the tabulated numerical values are rounded and he does not statistically evaluate the highest reversal floor and instead uses the top terminal floor as the reversal floor. He was thus unaware of Schroeder's 1955 work [5]. He does however suggest the design load of a car should be 80% of the Rated Load, see Table 2. In this case, the number of passengers in the car is determined by mass.

Using a spreadsheet, similar figures can be obtained using the data that Strakosch provides, see Appendix 1, column A. The average car occupancy is taken as 80% of the maximum occupancy according to Strakosch Table 4.2 and based on mass.

Strakosch later describes the required handling capacity for a group of lifts (pages 195 *et seq*) and suitable installations.

In his 1983 book he improves the tables to one place of decimals and argues for more space per person at 0.22 m^2 per person. The accepted value today is 0.21 m^2 per 75 kg person.

Table 1 Probable Stops (Strakosch Chart 4)

Passengers per trip

Upper floors served	10	12	14	16	18	20	22
18	8	9	10	11	12	13	13
16	8	9	10	10	11	12	12
14	7	8	9	9	10	11	11
12	7	8	9	9	10	10	10
10	6	7	8	8	9	9	9
8	6	6	7	7	8	8	8
6	5	5	6	6	6	6	6

Probable stops

Table 2 Lift Car Occupancy (Strakosch Table 4.2 -abstract)

Capacity (pounds)	80% Load (people)
2000	10
2500	12
3000	16
3500	19
4000	22

Table 3 Example of Strakosch calculation procedure

Taken from pages 68-70 of Vertical transportation: Elevators and Escalators, 1967

Incoming Traffic Calculations

Suppose we want to know how many persons a 3,500 lb elevator at 500 fpm with 3 ft, 6 in center opening doors, in an 11 storey building with 12-ft floor heights, can serve during a 5-min incoming traffic peak period.

1. Table 4.2, page 65, shows that the capacity of a 8500-lb elevator is 19 people.

2. The chart of probable stops, page 64, shows that 19 passengers will make approximately 9 stops on the 10 upper floors in this building.

Time to load 19 passengers (Table 4.2):	16.0 sec
Time to close 3 ft 6 in. center-opening doors and to start car (Table 4.8):	3.3 sec
Time to open the doors when the car returns to the lobby Table 4.4):	0.6 sec
Time to start the car and to stop the car when it returns to the lobby:	3.6 sec
3. The total time spent near the lobby:	23.8 sec
Time to open the doors at an upper floor stop:	0.6 sec
Time to transfer passengers at each upper floor stop: (Table 4.5):	1.8 sec
Time to close door at each stop:	3.3 sec
Time to start and stop at each stop:	3.6 sec
Total time spent at stopping and leaving each upper floor stop:	9.3 sec
4. Nine probable upper floor stops x 9.3 sec per stop equals total stopping time:	83.7 sec

5. Time to run back to first floor from top floor stop and to run from stop to stop exclusive of time required to get up to speed and to stop:

$$\frac{rise\ (10\ floors \times 2\ (up\ anddown) \times 60\ sec}{500\ fpm} = \qquad 28.8\text{ sec}$$

6. Total of all time factors equals round-trip time:	136.0 sec
7. Allowance for inefficiencies 5 percent of items 3 and 4:	5.4 sec
Total round-trip time:	141.4 sec
Or approximately:	141 sec

8. Elevator 5-min capacity:

$$\frac{19\ passengers\ per\ trip \times 300\ sec}{Round-trip\ time\ 141\ sec} = \qquad 40\text{ passengers}$$

In other words the single elevator in our example can serve 19 passengers in 141 sec or a total of 40 passengers in 5 min.

Item 7, a 5 per cent factor for inefficiency, is added to compensate for the rounding off of probable stops, door time, transfer time, and starting and stopping time and to simplify calculations. It could also be called a confidence factor representing the difference between our assumptions and possible actual conditions.

3.3 1972 - British Standard Code of Practice CP407

In 1972, the British Standard Code of Practice CP407, *Electric, hydraulic and hand powered lifts* was published. It contained selection tables, probably calculated by Frank Williams [6] using the Strakosch method and provided values of interval and handling capacity. Example 1 from CP 407 is shown in Table 4.

Table 4 Example from CP 407: 1972

Example 1. It is required to design a lift installation in an office building located in the suburbs of a provincial town. It has 8 floors above ground each with 3.3 m pitch (floor-to-floor distance) and 925 m^2 in net rentable area. The building will be let to a number of tenants whose starting and leaving times are unlikely to coincide. The population above the ground is given as 740. In the event of the population not being given it should be estimated on the basis of, say, 10 m^2 per person.

Estimated population above ground 925× 8/10 = 740 persons

Since the flow rate is not given it should be assumed as 12%.

Required handling capacity per 5 minutes to satisfy 12% flow rate:

740 × 12/100 = 89 persons per 5 minutes

The travel of the lift is floors above ground x floor pitch:

8 x 3.3 = 26.4 m

From Table 1 [not reproduced in this paper] the car speed required for 26.4 m travel for lifts in offices is 1.5 m/s.

Table 2 [reproduced in this paper as Table 5] performance data covers this example of a lift service to ground and 8 floors above, i.e. 9 floors.

CP 407, Example 1 uses a 12% uppeak arrival rate, which is the currently accepted value. Once the desired handling capacity has been calculated then the CP 407 Table 2 (see Table 5) is used, starting with the number of floors (N+1) to select the number of cars to meet a desired interval.

Example 1 is for a 9 storey building with a required handling capacity of 89 persons/ five minutes. A further table in CP 407 (not shown, Table 1 in that document) suggests three, 16 person lifts giving an interval of 39 seconds.

Many of the design parameters are not provided in CP 407. If following Strakosch then the average occupancy is 80% of the maximum based on mass. Using a spreadsheet a close correspondence for *HC*5 can be obtained see Appendix A, column B1. The actual %POP delivered is 12.6% and at that demand the interval is 41.1 seconds. If a match is made to 12% then the interval falls to 39.8 seconds, Appendix A, column B2.

Table 5 Passenger Lifts – Performance Data (CP 407: 1972 Table 2)

(Number of floors served: 6, 7, 8, 9). Based on 3.3 m floor-to-floor heights and lifts serving all floors. Standard cars and entrances as shown in BS 2655, Part3

Interval (seconds) / Handling capacity (persons)

	Number of cars	Speed (m/s)	10 passengers 750 kg	12 passengers 900 kg	16 passengers 1200 kg	20 passengers 1500 kg
6 floors	2	1.50	36 / 67	39 / 77	42 / 86	
	3	1.50		25 / 115	28 / 128	32 / 152
7 floors	2	1.50	41 / 59	44 / 68	48 / 75	
	3	1.50		28 / 102	32 / 113	36 / 135
8 floors	2	1.50	45 / 53	49 / 61		
	3	1.50		33 / 91	36 / 102	40 / 121
9 floors	3	1.50		36 / 84	$\boxed{39 / 93}$	44 / 110
	2	2.50		44 / 68	48 / 75	
	3	2.50		29 / 102	32 / 113	37 / 131

Note: The car sizes are integer values of passengers (persons) and load in kg, as persons times 75 kg precisely.

3.4 1975 - Barney and Dos Santos

In 1975 Barney and Dos Santos [7] developed and published the Round Trip Time (RTT) formula, which followed Strakosch's work, but including principles from the prior works reported by Gray as:

$$RTT = 2Ht_1 + (S+1)t_2 + 2Pt_3 \qquad (7)$$

This was the first formulised mathematical model.

This model continues to be widely used today, in a slightly different presentation, by most expert traffic designers, see Equation (4).

3.5 1984 - BS ISO 4190-6

In 1984 ISO published BS ISO 4190-6 "Lifts and service lifts (USA: elevators and dumbwaiters). Passenger lifts to be installed in residential buildings. Planning and selection". This standard contained selection charts, see Figure 1.

Note the standard only deals with residential buildings and for a passenger demand of 7.5% (%POP). All the user needed to know was the number of floors above the main floor, the population above the main floor and a desired interval. Three values of interval, 60, 80 and 100 seconds (Programme 60, Programme 80, Programme 100).

For example consider a 12 floor building with a population of 425 persons and a desired interval of 100 seconds. Using the chart then the lift installation could be either ④, ⑤ or ⑥.

Configuration ④ is one 630 kg lift and one 1000 kg lift.

Configuration ⑤ is two, 1000 kg lifts.

Configuration ⑥ is two, 400 kg and one 1000 kg lift.

This is where the human designer has to use their expertise in order to choose between the three possibilities.

These graphs are very broad-brush. For example, consider the Programme 80 without parking level. Take a building with 10 floors and a population of 400 persons. The suggested lift installation is ③, which is one 400 kg lift and one 1000 kg lift. However the same installation is also suggested for a building with 100 persons. If the handling capacity is precisely 7.5 % for 400 persons, then without a change of lift installation the handling capacity for 100 persons must be 30%.

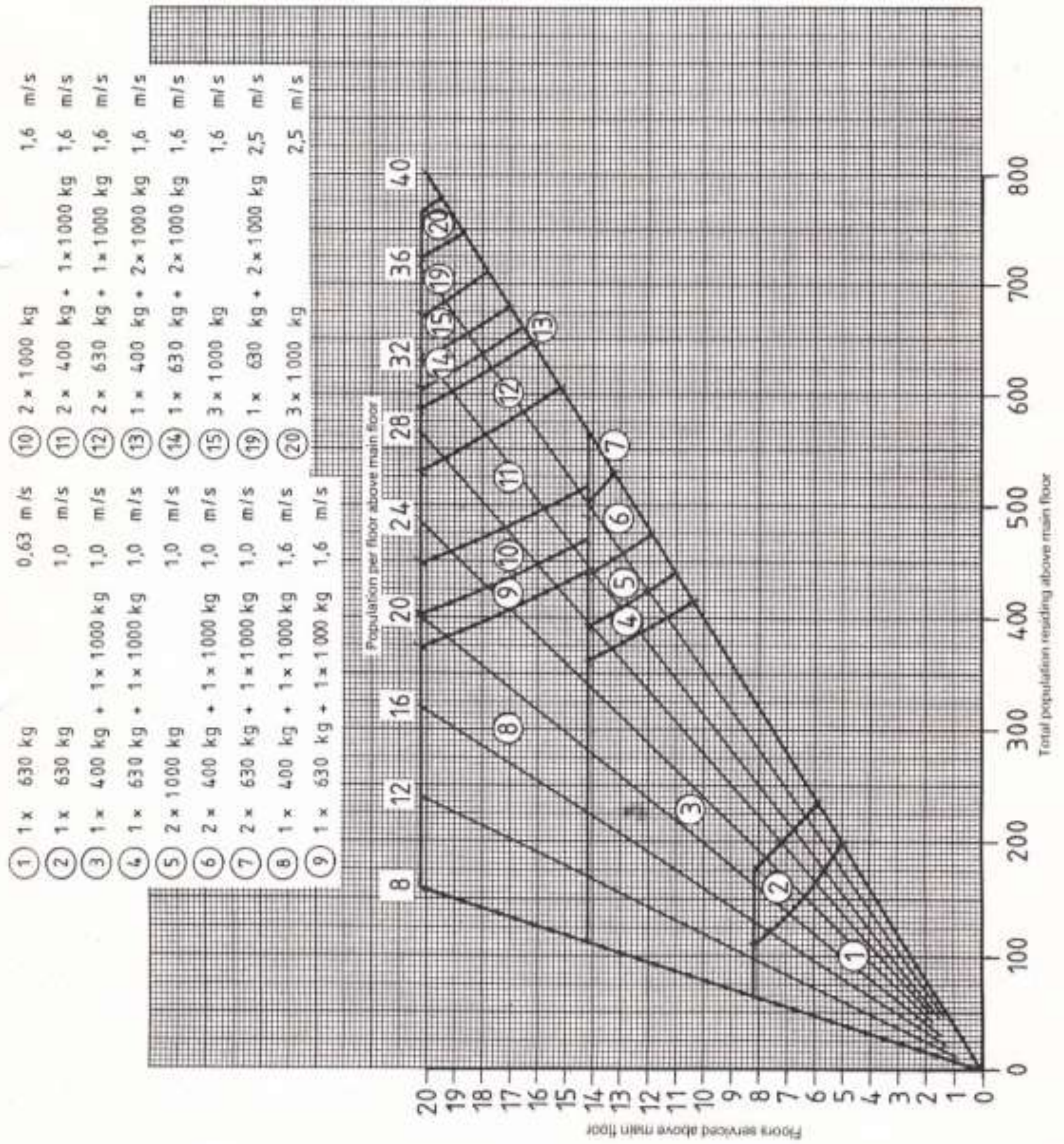
There are no details of the mathematics, but the procedures probably follow Strakosch. A peculiarity of the standard is the unequal rated load combinations. These graphs were often used by lift industry sales people.

An important point is the ISO 4190-6 standard states clearly in its Table 2 that the average car occupancy is to be 80% of the maximum based on rated load (mass).

ISO 4190/6-1984 (E)

Annex C

Programme 100, without parking level



5

Figure 1 Selection graph from ISO 4190-6: 1984

3.6 1988 - Elevator Micropedia

In 1988 the first edition of the Elevator Micropedia [8] was published. This included a "Ready Reckoner", see Table 6. The lift industry has been and still is a very pragmatic industry and mathematics is an art few are comfortable with. Hence the inclusion of a ready reckoner.

The ready reckoner was developed for the performance of one lift and automates the calculation of the round trip time. All the necessary input data is specified.

Table 6 Sample page from Elevator Micropedia 1988

RTT TABLE: 6 to 13 person cars; 3 to 13 floors above main terminal 8

CC		6 person 450kg			8 person 630kg			10 person 800kg			13 person 1000kg		
N	v	RTT	ΔT	δt	RTT	ΔT	δt	RTT	ΔT	δt	RTT	ΔT	δt
3	0.63	56.5	3.6	1.1	61.4	3.8	1.1	65.5	3.9	1.1	70.9	4.0	1.1
3	1.00	52.4	3.6	0.7	57.4	3.8	0.7	61.6	3.9	0.7	67.0	4.0	0.7
4	0.63	67.5	4.0	1.8	73.7	4.4	1.7	78.7	4.6	1.7	85.0	4.8	1.6
4	1.00	60.9	4.0	1.1	67.3	4.4	1.1	72.5	4.6	1.1	79.0	4.8	1.0
5	1.00	68.4	4.3	1.6	76.1	4.8	1.5	82.4	5.2	1.5	90.0	5.5	1.4
5	1.60	62.4	4.3	1.0	70.4	4.8	1.0	76.8	5.2	0.9	84.7	5.5	0.9
6	1.00	75.4	4.5	2.1	84.2	5.1	2.0	91.3	5.6	1.9	100.2	6.1	1.8
6	1.60	67.6	4.5	1.3	76.6	5.1	1.3	84.1	5.6	1.2	93.3	6.1	1.1
7	1.00	82.0	4.7	2.6	91.7	5.4	2.6	99.7	6.0	2.4	109.6	6.6	2.3
7	1.60	72.3	4.7	1.6	82.3	5.4	1.6	90.7	6.0	1.5	101.0	6.6	1.4
8	1.60	76.8	4.8	1.9	87.6	5.6	1.9	96.7	6.3	1.8	108.1	7.0	1.7
8	2.50	69.8	4.8	1.2	80.8	5.6	1.2	90.1	6.3	1.2	101.9	7.0	1.1
9	1.60	81.0	4.9	2.3	92.5	5.8	2.2	102.3	6.5	2.1	114.7	7.4	2.0
9	2.50	72.9	4.9	1.4	84.6	5.8	1.4	94.6	6.5	1.4	107.4	7.4	1.3
10	1.60	85.1	5.0	2.6	97.2	5.9	2.5	107.6	6.7	2.5	120.9	7.7	2.4
10	2.50	75.8	5.0	1.7	88.1	5.9	1.6	98.7	6.7	1.6	112.4	7.7	1.5
11	2.50	78.6	5.0	1.9	91.4	6.0	1.8	102.6	6.9	1.8	117.1	7.9	1.7
11	3.15	74.8	5.0	1.5	87.6	6.0	1.5	98.9	6.9	1.4	113.6	7.9	1.4
12	2.50	81.3	5.1	2.1	94.6	6.1	2.1	106.2	7.0	2.0	121.5	8.1	1.9
12	3.15	77.0	5.1	1.6	90.3	6.1	1.6	102.1	7.0	1.6	117.6	8.1	1.5
13	2.50	83.9	5.1	2.3	97.6	6.2	2.3	109.7	7.1	2.2	125.7	8.3	2.1
13	3.15	79.2	5.1	1.8	92.9	6.2	1.8	105.1	7.1	1.8	121.3	8.3	1.7
tp±0.2s		±1.9 s			±2.6 s			±3.2 s			±4.2 s		

The ready reckoner offers the user the opportunity to vary the "cycle time" (today called "performance time") by ±1.0 s, the interfloor distance by ±10% and the passenger transfer times by ±0.2 s.

Example

Find the handling capacity of a lift system serving a ten floor building with a 10 person car (contract capacity 800 kg), a contract speed of 2.5 m/s, a performance time (T) of 9.0 s, an interfloor distance of 3.0 m and an assumed passenger transfer time of 1.2 s.

Using the Table find N =10 and v = 2.5 in the left hand column.

Follow across the page until the column for CC = 10 is reached. The RTT is shown as 98.7 s.

As T is 9.0 s subtract the value under ΔT column (6.7 s).

As d_f is 3.0 m subtract the value under the δt column (1.6 s).

As t_p is 1.2 s add the value at the foot of the column (3.2 s).

Thus the final value for RTT is 93.6 s (98.7 – 6.7 – 1.6 +3.2).

Using equation (3)

$$HC5 = \frac{300 \times 8 \times 1}{93.6} = 9.6 \text{ persons/5-minutes}$$

Note the number of passengers in the car are by mass, not area.

The ready reckoner tables were included in CIBSE Guide D: 1993[9]. They did not appear in CIBSE Guide D: 2000 as by then calculations were being carried out where the average number of passengers in a lift car was determined by area not mass.

4 PASSENGER CAPACITY BY MASS OR AREA?

Passengers will not usually board a crowded car, especially if the other passengers are strangers. Strakosch in his 1967 book observed the loading of lift cars did not meet the assumed loading based on weight. Fruin [10] (1971) drew a person template with a body ellipse of 600 mm by 450 mm, which is 0.21 m^2. Thus an anomaly between the stated passenger capacity (in persons), displayed on the in-car rating plate and the actual number of passengers observed in a car developed. In 1993 edition of CIBSE Guide D[9], an actual value for passenger capacity was shown in Table 3.4 based on a body ellipse of 0.2 m^2 and a 5% reduction for handrails, etc., ie: 0.21 m^2.

Perceptively the ISO Technical Report ISO/TR 11071-2, 1996 [11] [repeated in 2006] said:

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

The scepticism of this change from mass to area in calculating car occupancy gradually disappeared as various designers [12][13] confirmed it. The latest editions of the British Council of Offices guidelines [14] recommend area based car selection.

Calculation of the number of passengers by area rather than by mass is now accepted best practice, used in the industry *de facto* standard simulation software [15] and readily available spreadsheets [16]. All competent traffic designers now use area.

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

5 2014 - REVISION OF ISO 4190-6: 1984 {ISO 8100-32}

In 2014 the International Standards Organisation, Technical Committee 178, formed Sub Group 5 in its Working Group 6, to revise BS ISO 4190-6: 1984. WG6 takes the view that equations and the design process is too difficult for a lay person to apply. SG5 has published revised versions of the charts of 1984 for public comment and extended them to include offices and hotels. Consider Figure C.1 (shown as Figure 2) in the draft sent out for comment in 2018.

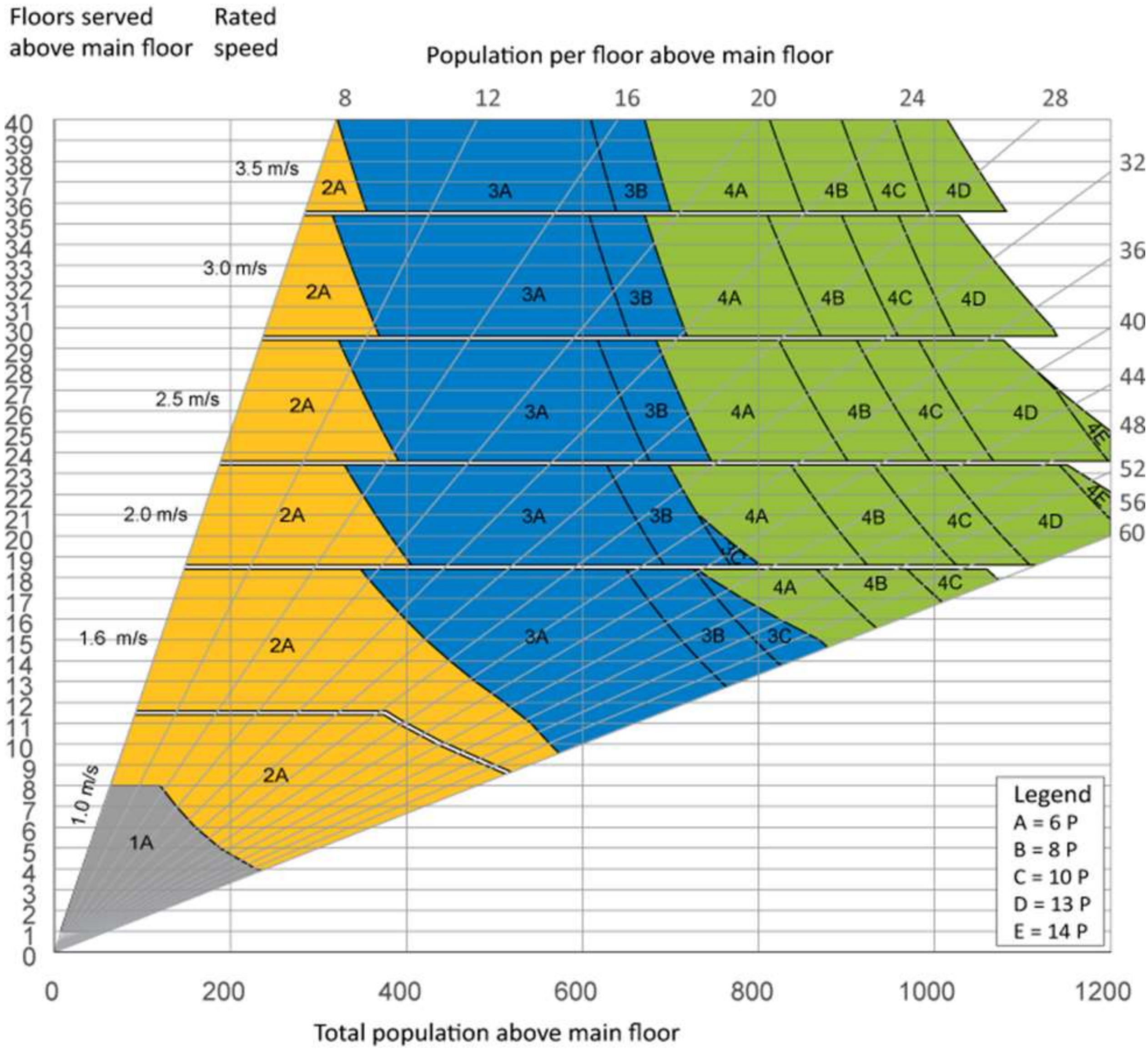


Figure 2 Figure C.1 from draft ISO 8100-32

The charts are created following the methodology presented by Ruokokoski and Siikonen [17].

Note: the calculation used for these charts is based on formulae in the draft ISO 8100-32 rather than those given in this paper.

The charts are complex to draw, which is reflected in the simplification of the inputs selected. For example, a 2.0 m/s lift is only considered for buildings with 19 to 23 floors; it would not be unreasonable to consider a 2.0 m/s lift for an 18-floor building. This could mean the designer selects a four-lift solution when a three-lift solution would be adequate.

Regions overlap, so choosing which region is displayed is a matter of judgement. For example, the 1A region is cut off at 8 floors. In fact, it continues, up to 10 floors, hidden by the 2A region. So, for a building with 10 floors served above the main terminal and a total population of 100, one 6-person lift meets the criteria, but the graph is suggesting two 6-person lifts.

Another challenge when creating these graphs is that some regions are too small to be labelled.

An approach which plotted the boundary lines rather than regions would have the advantage of not hiding prospective solutions from the user [20].

6 2017 - PROPOSAL – GRAPHS BASED ON *P* THE AVERAGE CAR LOADING

Much of this discussion has been dominated by the number of persons that need to be accommodated (by area) in the lift car. Once the number of passengers to be accommodated is known then a suitable sized lift car can be selected from Table 7.

Table 7 Rated load, maximum available car (platform) area, maximum passenger capacity (P_{max}) and average passenger capacity (P)*

Rated load (kg)	Maximum available car area (m^2)	Passenger capacity P_{max} and P by area @ 0.21 m^2 per person	
		P_{max}	P
450	1.30	6.2	5.0
630	1.66	7.9	6.3
800	2.00	9.5	7.6
1000	2.40	11.4	9.1
1275	2.95	14.0	11.2
1350	3.10	14.8	11.8
1600	3.56	17.0	13.6
1800	3.88	18.5	14.8
2000	4.20	20.0	16.0
2500	5.00	23.8	19.0

* P = 80% of P_{max}. Assumes a capacity factor of 80%.

However, most designs start with the number of floors in a building and the population. This has led to the development of the chart shown in Figure 3. This chart has been produced manually.

For example, suppose a lift installation is to be selected for an office building with eight floors above the entrance floor and a population of 2000 persons. The circled result shows that there is a choice of either 8 x 1800 kg (which is about right) or 8 x 2000 kg (which provides extra capacity) or 7x 2500 kg (which requires less lifts).

7 2017 - A BASIC EXPERT SYSTEM

Barney, Peters and Dean [18] produced a set of tables using an expert engine with a range of parameters to include in an alternative draft for ISO 8100-32 [19]. The expert system mimics a design methodology specified by Barney, incorporating design choices made where guides and standards require the reader to interpret a requirement or make a choice. The process of developing the expert engine itself took several iterations as additional rules were added to account for judgements the designer is called to make in the design process. The creation of this expert system is discussed in the paper *Expert Systems for Lift Traffic Design* [20].

8 CONCLUSIONS

The selection of a lift installation requires mathematical modelling, experience and judgement. Reducing the whole selection process to a graph, table or software requires choices and assumptions to be made by the person creating the tool. These assumptions may be incorrect even for the most sophisticated expert system unless the expert has ensured the software is asking all the right questions, and all assumptions made are fully understood by the person using the tool.

De-skilling engineers by providing graphs, tables and expert systems has risks. Yet hiding the mathematics and encapsulating experience and judgement in a design tool is repeatedly called for, and the development of increasingly sophisticated expert systems is inevitable. In an industry where “experts” often do not agree, expert systems will also not agree.

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BIOGRAPHICAL DETAILS

Dr Gina Barney Principal of Gina Barney Associates, English Editor of Elevatori, Member of the Chartered Institution of Building Services Engineers (CIBSE) Lifts Group Committee, Member of the British Standards Institution (BSI) Lift Committees, UK expert to two International Standards Organisation groups. Dr Barney is the author of over 100 papers and is the author, co-author or editor of over 20 books. She has the degrees of BSc, MSc and PhD and the professional qualifications of CEng, FIEE, HonFCIBSE and Eur.Ing.

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

Appendix A - Spreadsheet Examples

	A	B1	B2
INPUT DATA	**Value**	**Value**	**Value**
Number of floors	10	8	8
Rated load	1590	1600	1600
Actual car capacity	21	16	16
Number of passengers	19	12.8	11.8
Number of lifts	1	3	3
Rated speed	2.5	1.5	1.5
Building population	180	740	740
Interfloor distance	3.6	3.3	3.3
Express jump	0	0	0
Express additional time	0	0	0
Single floor flight time	5.1	4.9	4.9
Door close time	3.3	3.2	3.2
Door open time	0.6	2.5	2.5
Advance door opening	0	0	0
Start delay	0.85	0	0
Passenger transfer time	0.84	1	1
RESULTS	**Value**	**Value**	**Value**
Number of passengers	19.0	12.8	11.8
Highest reversal floor	9.85	7.79	7.76
Number of stops	8.65	6.55	6.35
Performance time	9.9	10.6	10.6
Round trip time	141.4	123.3	119.4
Interval	141.4	41.1	39.8
Handling capacity	40	93	89
Percentage population	22.4	12.6	12.0
Capacity factor (%)	90	80	74
Uppeak average waiting time	161	35	28
Down peak handling capacity	63	146	139
Midday peak handling capacity	48	118	113

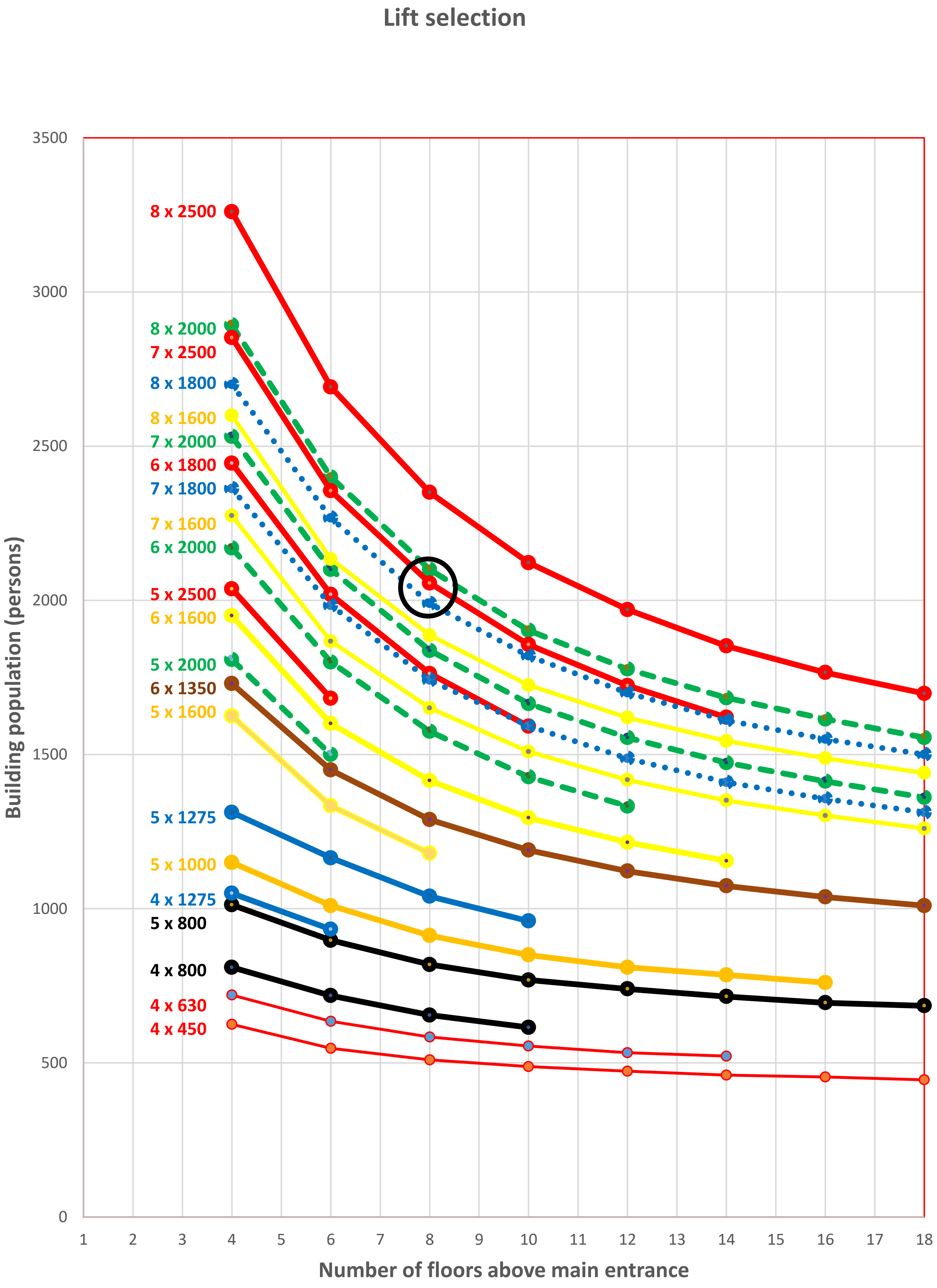

Figure 3 Example graphical presentation of expert system results

The Optimization of a Learning and Training Portfolio at a Multinational Lift Manufacturer

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Keywords: learning, training, adult education, training portfolio, lift engineering

Abstract. The seed campus organization, a learning provider with hubs and satellites in each region of the business, is the global, sole learning provider at the multinational Lift Manufacturer for business-specific and business-adopted training. However, due to different histories of each core hub (Asia Pacific, Europe/Africa and North America), the learning offerings differ from region to region. In addition, Education Technology is evolving at a dramatic pace, which requires an agile design approach for training programs and courses. This paper looks into the current state of that lift and escalator engineering training & learning curriculum.

It examines the fundamental pedagogic design principles as well as the latest lift engineering requirements and technology trends to develop relevant and up-to-date Adult Learning strategies. The paper concludes with recommendation to improve the seed campus curriculum catalogue to ensure that the current expectations from the internal user group and the business are met.

1 INTRODUCTION

Learning is essential to supporting and enhancing the capability of any business organization, and a skilled and well-educated workforce can be described as its backbone and key success factor. The efficient and effective set-up of corporate learning programs is essential, especially when it comes to maximizing the cost and productivity.

Considering the high expense of corporate learning programs, businesses need to find new ways to develop their workforce on one hand, while on the other hand optimizing the total spend on learning programs in general. The strategic curriculum optimization helps companies offer training in line with business strategy. That optimization approach requires a solid structural analysis of the following prerequisites:

- A unified Competency Model or Skills Matrix (as an underlying foundation) is available for each business function
- Learning Needs are analyzed based on business function strategy and therewith define the competencies
- Synergies between curricula of learning providers and business functions are identified to minimize the area of training operations and to optimize the Return on Investment (ROI)
- Training courses are conducted in the way that workforce competency levels, the overall productivity and individual variety of skills are maximized. Therein suitable forms of training, such as classroom training, eLearning or Webinars and e.g. Virtual Reality training approaches are used to ensure the best individual fit in regards to learning styles [8].

2 SEED CAMPUS OVERVIEW

The overarching curriculum of the Corporate Enterprise operates through seven global 'Functional Campuses': Leadership, Controlling/Accounting/Risk (CAR), Communication (COM), Human Resources (HR), Project Management (PM), Procurement and Supply Management (PSM), Sales and Strategy, Markets & Development (SMD). The program comprises courses offered via four 'Regional Learning Centers' (RLC) [1]. There is a very broad range of training courses available within the program which covers leadership skills, a selection of functional skills as well as some general / other areas.

The functional skills are Business Area (BA) specific, which includes the Elevator and Escalator Technology (E&ET) area.

The core engineering training is delivered through the Global Engineering Training Program (GETpro). This program is primarily designed for the Research and Development (R&D) community, but it could possibly provide training across other technical staff areas. GETpro is an engineering core program of the seed campus curriculum. The seed campus organizational structure is shown in Figure 1 below.

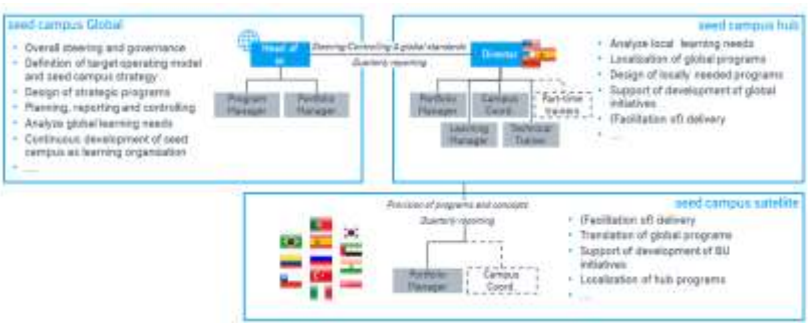

Figure 1 Seed campus organizational structure

3 COMPETENCY MODEL AND LEARNING NEEDS ANALYSIS

Learning Provider or Business Function curricula make a difference if they are designed to fill the gap between the workforce competencies and aligned to strategic business needs (Learning Needs Analysis).

3.1 Competency Model or Skills Matrix

A competency model determines tasks and function-specific competency levels (description of certain tasks a profile is required to perform). To be able to qualify employees to perform a specific task (e.g.: to manage a business process or apply a specific computer application), enterprises have to compare individual competency profiles with the required competencies (as shown in Figure 2).

Figure 2 Spider Chart of Skills Matrix

Such a competency model provides a method to consistently outline competency profiles. It helps to analyze organizational and position-specific needs, existing capabilities to derive learning objectives of individual training courses or modules.

3.2 Learning Needs Analysis

The purpose of a Learning Needs Analysis (LNA) is the systematic approach to determine training needs (→ What training needs to be offered?) and it considers the following aspects – in addition to the discussed business needs and competencies:

- Training Forms (What training methods fit best to the needs of the learner?). For example [8]:
    - On-site classroom training
    - eLearning
    - Videocasts
    - Massive Open Online Course (MOOC)
    - Physical simulator training
    - Augmented reality / Virtual reality / Mixed reality training
    - Micro Learning
    - Blended learning forms
- Cost (How much budget is available to develop and offer a specific measure to a group of learners?). Learning costs are typically broken down into the following cost categories:
    - Development cost (internal/external consultants, material, Intellectual Property, travel)
    - Travel cost (for learners and teachers)
    - Proportionate salaries of teachers and learners
    - Rent for buildings and physical environments
    - Technical equipment
    - Marketing expenses
- Effectiveness of training measures.
  Basically, it is the Return on Invest (ROI) that measures the effectiveness best, as organizations will not spend time and money on training that does not have an impact.
  Further to the established Kirkpatrick Model [9] with four levels of training evaluation:
    - Reaction (level 1): Learners appraise the training in regards to their engagement and job relevance,
    - Learning (level 2): Learners evaluate the training in regards to acquired knowledge, skills and attitude,
    - Behavior (level 3): Learners actually apply what they have learned during the training back in their jobs,
    - Results (level 4): Degree to which the intended/aimed outcomes are demonstrated as a training result

  The following guiding questions have to be answered to evaluate the effectiveness of training measures:
    - What is the long-term impact of the training measure to the individual learner or group of learners?
    - Did the training help to improve abilities and fill skill gaps?
    - Do the learners apply what they learned and did their work performance improve?

A Learning Needs Analysis (or sometimes called Training Needs Analysis,) evaluates kinds and volumes of training required by the business functions, taking strategic objectives and operational needs into account.

4 ENGINEERING TRAINING PROGRAM STRUCTURE

GETpro has a modular structure. According to the module specification [1] each module is defined by ‘Learning Goals’, ‘Content’ and ‘Methodology’. The ‘Key facts’ section provides additional information, such as the language of instruction, expected entry requirements, for whom the module is designed for (the ‘target group’), indicative numbers of the participants (‘group size’), the duration and learning materials (‘documentation’).

This can be broadly mapped onto a standard module specification structure used at UK Higher Education (HE) institutions.

For example, at the University of Northampton (UoN) the module specification documentation involves the following key components

- Pre/co-requisites
- Module overview
- Indicative content
- Learning outcomes
- Learning, teaching activities/ time/ hours
- Assessment activities / hours
- Alignment of learning outcomes and assessment

In this context, it appears that the seed campus module structure would benefit from a clearer assessment strategy. In terms of education standards there are two main principles in assessing for learning quality [2]: formative, to provide feedback during learning; and summative, to grade learners so that an index of how successfully the learner has performed when the teaching and learning (T&L) activities have been completed is defined.

To provide the necessary rigor in the GETpro program (Figure 3 shows the structure of the program) relevant activities are considered be introduced as a post-event summative assessment, such as on-the-job assessment (check, that learners apply what they learned). In addition, formative assessment elements could be introduced as pre-event activities. This strategy would be designed to ensure the assimilation, at the appropriate level, of a body of knowledge necessary in the achievement of the outcomes for each GETpro module.

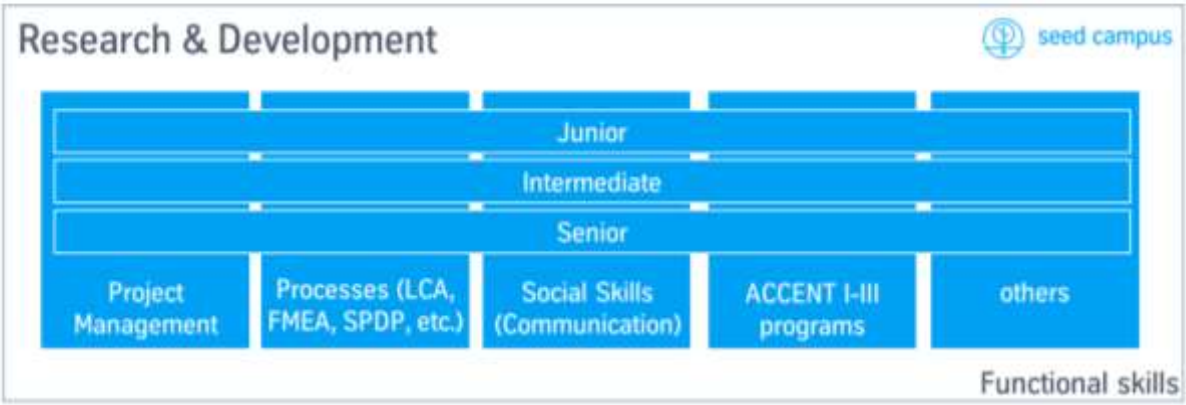

Figure 3 GETpro structure (principle)

5 TEACHING AND LEARNING METHODOLOGY

The GETpro program is delivered through a range of T&L methods. Those include mainly traditional face-to-face (on-campus / classroom) activities such as presentations, workshops, and group work. Modern Educational Technology (EdTech) such as e-learning (via web conference) is also applied.

The advantage of ET is its ability to engage learners in their own time and activities that might be difficult to implement in the traditional classroom mode. The interactive use of ET can involve both synchronous activities (in the same timeframe) and asynchronous (communication takes place in one's own time). Those can involve, for example, interactive simulation tools, virtual classroom environments, discussion boards. The latest trends and developments include the use of tools powered by Artificial Intelligence (AI) [3] such as chatbots in learning and development for employees [4]. These appear to be opening new avenues for advanced ET techniques.

ET involves also distance (or off-campus) learning (DL)/ teaching. The UoN has developed and has been offering lifelong learning (LLL) / adult learning (AL) DL program in E&ET for over 30 years. Historically, it was initiated following the introduction of the first edition of the European standard EN 81-1:1977 (introduced in the UK as BS 5655-1:1979) [5]. The UK Lift Industry needed a wide ranging re-education of its workforce in both the Design and Field service. The need to update the workforce was recognized by the then National Association of Lift Makers (NALM), now the Lift and Escalator Industry Association [6]. They also recognized that due to the wide geographic dispersion of potential students, (DL was possibly the best mechanism for delivery [7].

In this context GETpro would benefit from the DL mode being combined with the traditional face-to-face (conventional classroom) methods. Students could then engage in learning more effectively.

The multi-national nature of the seed campus program raises further issues. Difficulties in teaching international students in HE are well known and are often seen as 'cultural' in origin (such as reliance on rote learning and passivity) [2]. But bearing in mind the professional caliber and international experience of GETpro adult learners, this does not lead to adverse problems in engagement in effective learning. However, the fact that learners come from different cultural backgrounds sometimes leads to some difficulties that can be minimized through innovative T&L methods.

6 POTENTIAL AREAS OF IMPROVEMENT TO THE CURRICULUM

The key success factors of any learning curriculum are business relevance and efficiency and effectiveness.

Therefore, and to ensure a successful learning curriculum, it is essential to double-check the relevance of the offered content with respective stakeholders and customers on a regular basis.

On the other hand, the guiding question should be: What can be done to make Learning more effective and (cost) efficient. In that regard, Education Technology (EdTech) is key to success:

- Mobile devices and mobile applications support and help prepare the learner for the next career step
- Bringing EdTech into the classroom is an effective method to engage with the learner in all learning styles.
- EdTech gives learners the opportunity to enhance the interaction and collaboration with their network.
- EdTech gives teachers the opportunity to develop a digital literacy across all ages and experience levels (of a multi-national, global lift manufacturer).
- Integrating EdTech in learning & development helps learners to stay engaged. However, in Distance Learning, the instructors miss the opportunity to observe whether learners are recording the content by taking notes. In classroom training this indicates activity and attention.

As EdTech in OLEs does not provide this essential feedback, digital learning content is usually designed in short chunks to ensure not to collide with the attention span of an individual.

- Combining new EdTech like Virtual Reality with traditional Instructor-led-training (ILT) is one example to introduce new technology into the learning experience
- With EdTech, the traditional *passive* learning model breaks up, as classroom or mobile technology changes the role of the teacher into the direction of an encourager, adviser or coach.

7 CONCLUSION

The seed campus curriculum portfolio comprises of a comprehensive set of courses. The structure of the portfolio involves diverse learning schemes and modules which is designed for the modules to complement each other

For example, considering the 'Accelerated Engineering' training scheme offered at two levels, with ACCENT2 designed for technical R&D staff with 1-5 year experience and ACCENT3 aiming at a more senior level (specialist/ managerial) staff.

The scheme facilitates contribution from other modules and thus accelerating the staff training process. The ACCENT2 requirements stating 'Basic understanding of elevation systems technology' sounds a bit vague and stating pre-requisites more clearly might be of benefit.

Education Technology transforms the learning experience and generates a huge amount of new opportunities:

With the consideration of a learner-centric approach (e.g. Open Learning Environments) and different learning styles [8], newest technology and the fact that knowledge and learning sources are available 24/7 can revolutionize learning and development in Higher Education.

Especially the customization of the learning experience according to individual learning preferences will increase the efficiency of learning.

It is recommended to put some emphasis into the analysis of the learning population to be able to offer learnings that are the best possible fit to learners needs.

These aspects should be taken into consideration for the next generation of the seed campus curriculum.

The success of these new ways of teaching of the next generation of the seed campus curriculum should be investigated and measured, for instance with a study that compares the old learning experience with the new learner-centric approach.

Different cohorts with different learning styles and cultural background should be an ideal user group for an online questionnaire assessment.

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BIOGRAPHICAL DETAILS

Thomas Ehrl has worked for thyssenkrupp Elevator AG, Germany since April 2008, and has been Head of seed campus Global of thyssenkrupp Elevator AG, Essen; Head of Research & Innovation Center of thyssenkrupp Elevator Innovation GmbH, Rottweil; Engineering Training Manager at Corporate Level of thyssenkrupp Elevator AG and Manager R&D Project Standards at Corporate Level of thyssenkrupp Elevator AG. He is a Mechanical Design Engineer (receiving his degree in 1994), a part-time PhD student with the School of Science and Technology of The University of Northampton, and his professional career started in 1994. He is married with one son of 16 years old. His interests include travelling, mud races, running, soccer, music, vintage English motor cycles and networking.

Stefan Kaczmarczyk has a master's degree in Mechanical Engineering and he obtained his doctorate in Engineering Dynamics. He is Professor of Applied Mechanics and Postgraduate Programme Leader for Lift Engineering at the University of Northampton. His expertise is in the area of applied dynamics and vibration with particular applications to vertical transportation and material handling systems. He has been involved in collaborative research with a number of national and international partners and has an extensive track record in consulting and research in vertical transportation and lift engineering. Professor Kaczmarczyk has published over 90 journal and international conference papers in this field. He is a Chartered Engineer, being a Fellow of the Institution of Mechanical Engineers, and he has been serving on the Applied Mechanics Group Committee of the Institute of Physics.

Jonathan Adams graduated from the University of Bradford in 1990 with a B.Eng. degree in Electrical and Electronic Engineering. He holds a Certificate in Education from the University of Leicester, and an M.A. in Continuing Education from the University of Warwick. He also holds a PhD in Engineering Education. His industrial background is in the lift-making industry where he spent nearly 10 years. He has been employed at The University of Northampton for over 20 years specialising in distance education for the lift industry. He is currently Head of Department of Engineering & Technology. His research interests include teaching and learning strategies used in continuing and engineering education, and in the use of electronic methods for delivery, assessment and support. He is a Teaching Fellow of The University of Northampton.

Benedikt Meier received his Diploma in Mechanical Engineering from the University of Hannover, Germany. In 1992, he obtained his doctorate in Cold Testing of combustion engines. In thyssenkrupp Elevator AG, he is leading the Global Project Management Office (PMO). Since July 2015, he serves as Visiting Professor in the School of Science and Technology at the University of Northampton. His expertise is in the area of horizontal and vertical transportation and material handling systems. In addition, he is an internationally recognized expert in Project and Program Management. Professor Meier has published several journal and international conference papers in his area of expertise.

The Space Elevator Concept and Dynamics

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Keywords: space elevator, carbon nanotubes, access to space

Abstract. The Space Elevator or Space Lift is a radical technology for accessing space and the ultimate Earth-bound slender structure. The concept was first published in 1960 and was subsequently popularized in science fiction stories. After the discovery of carbon nanotubes in 1991 and subsequent calculations and measurements of their strength, the Space Elevator concept moved from the realm of science fiction to science possibility.

The Space Elevator is conceived to be a carbon nanotube ribbon stretching from an Earth station in the ocean on the equator to far beyond geosynchronous altitude. This elevator co-rotates with the Earth. Climbers ascend the ribbon using power beamed from Earth to launch spacecraft in orbit or to other worlds. The requirements of the ribbon material, challenges to the building of the space elevator, deployment, oscillations, design variations and the promise of the space elevator are briefly discussed in this paper.

1 INTRODUCTION

This paper begins with a description of the space elevator (SE) based upon the conceptual outline described in the book, *The Space Elevator*[1] by Edwards and Westling. This concept involves a meter-wide carbon nanotube (CNT) ribbon thinner than a sheet of paper that extends from a point on the Earth's equator to 100,000 km above that point to a counterweight. To use the ribbon to access space, mechanical climbers ascend the ribbon laden with payloads. Power for these climbers is expected to be beamed from the ground in the form of infrared, laser energy.

The center of mass of the system resides near geosynchronous altitude, thus the system co-rotates with the Earth. The counterweight, in uniform circular motion around Earth, provides a restoring force. At geosynchronous altitude the ribbon is widest because the forces are greatest. Below geosynchronous Earth orbit (GEO), the net force on a ribbon segment is toward the earth and the tensile strength of the segment must support all below it. For a ribbon segment above GEO, the net force is away from Earth and a segment must hold all segments beyond itself. As a climber ascends the ribbon, tension in the ribbon provides a restoring force that continually increases the angular momentum of the climber.

The SE system is analogous to a railroad and is subject to the economy of scale. Once the rails are laid, the cost to transport across the system is low. Chemical expendable rockets cost approximately $10,000 per kilogram to low Earth orbit (LEO). With the SE system, it is expected that the cost to LEO would fall by a factor of 3 with the first elevator, and later fall by factors of 10 and 100 as a space elevator infrastructure of larger capacity elevators are constructed. The cost to middle Earth orbit (MEO) and GEO would decrease by a greater factor. This dramatic drop in launch costs enabled by a space elevator infrastructure will enable the exploitation of space to solve Earth's problems.

The SE is a new paradigm for accessing space and as such is an enabling technology. Commerce in space including power generation, tourism, manufacturing, mining and commercial/government exploration will be developed because transportation will have dropped to a small part of the cost of the enterprise.

2 HISTORY AND MATERIALS

Many individuals may have conceived of an SE since the concept is a part of human consciousness. The Tower of Babel, Jack and the Beanstalk and references to “stairways to heaven” have existed for a long time. More recently, the academician, Konstantin Tsiolkovsky, a Pole living in Russia around 1895, wrote of towers extending from Earth up into the cosmos while visiting Paris and seeing the Eiffel Tower. In 1945, Sir Arthur C. Clarke patented the geosynchronous satellite and pointed out its usefulness for communications. There is a report that an American, John McCarthy, studied a “Skyhook” in the early 1950s.

The first published discussion of an SE-like structure was by the Russian engineer Yuri N. Artsutanov[2]. In 1960 he published a short article in *Pravda* for children. The concepts and numbers presented in this article make it clear that he understood the concept and had done calculations to back up his statements. The first journal article was published by four scientists from Woods Hole Institute[3] in 1966. Presumably the long cables that oceanographers used to explore ocean trenches inspired the authors to apply this technology to space. The last person to discover the space elevator was Jerome Pearson in 1975. Pearson published the most detailed physical study[4] at that time and has continued to investigate the concept up to the present.

These discoverers understood the promise of the SE. But they all recognized that no material existed that was strong and lightweight enough to manufacture the SE ribbon and make the SE a reality. Therefore, the SE existed in many forms in science fiction for many years[1].

In 1991 Iijima[5] discovered carbon nanotubes. CNTs have been reported theoretically to possess a tensile strength in the range of 300 GPa[6-7]. The Earth SE ribbon requires around 100 GPa of tensile strength minimum[1]. An actual ribbon would be built with strength contingency so consider 130 GPa or higher as the required strength. Thus, this new CNT material offers, for the first time, the possibility of building an SE ribbon.

В космос —
НА ЭЛЕКТРОВОЗЕ

Figure 1 The first Space Elevator article in Pravda

A macroscopic SE ribbon could be formed with CNTs by spinning individual fibers or by forming CNTs into a composite material. CNTs are essentially inert and do not want to form bonds between them. Only weak, ionic Van der Waals bonding operates between the individual CNTs. Its source is the electrical "landscape" on the surface of a CNT and are additive in the sense that the more and more regions along a CNT that are experiencing Van der Waals forces, the stronger the overall attraction. Spinning of nano-scale CNTs requires long tubes (possibly millimeters or centimeters) so that the weak Van der Waals forces are effective over a length sufficient to provide strong bonding between tubes. Handling nano-scale fibers is a challenge so spinning CNTs into micron size threads is another option. Using CNT composites to form the ribbon possess other challenges that include the chemical bonding of the CNTs to a matrix material, achieving uniform distribution of CNTs throughout the matrix and the alignment of the CNTs in the matrix.

Whatever technique is adopted for the SE ribbon, the process must be adaptable to manufacturing so that 100,000 km of ribbon can be fabricated in a timely fashion. Indeed, realizing the fantastic physical properties of a single CNT in a macroscopic assemblage of CNTs is currently impossible, but undergoing intense research. Currently, CNTs are an expensive material from which to make any macroscopic object because a typical cost for 5 micrometer long, single walled CNTs is around $12 per gram! The cost of CNTs must drop dramatically before an 800-ton SE cable can be manufactured cost effectively.

3 DEPLOYMENT SCENARIOS

In 1999 NASA held a conference on the SE. The scenario that emerged from the meeting was similar to Arthur C. Clarke's scenario in the Fountains of Paradise: an asteroid would be captured and placed into GEO around the earth. The carbon on the asteroid would be used to build a massive, CNT tower from the asteroid down to Earth's surface. Four magnetically levitated trains would run up the tower at very high speeds, delivering people and cargo to the GEO station. The asteroid would end up slightly above GEO to preserve the center of mass residing at GEO and would act as a counterweight. One estimate of the time to realize this vision was 300 years! As an astronomer, the author of this paper can assure you that it would take at least 300 years to convince astronomers to let a large asteroid that close to the Earth!

Now there is a "bootstrapping method" being developed for the deployment of the first space elevator – a major effort no matter the method used. The basic plan is to launch the components, deployment spacecraft and pilot ribbon, into LEO. This will take many launches as even a narrow (about 20 cm) ribbon and its deployment spacecraft are massive. Modern rocket launch vehicles do not have the capacity to carry such massive payloads to LEO in a single launch. In LEO the system is assembled possibly with the help of astronauts. Then the system must be lofted to GEO above the desired point on Earth, probably the ocean on the equator about 300 km west of the Galapagos Islands.

Two possible scenarios are being considered to thrust the system to GEO. The first scenario is to launch all the fuel to LEO and use an efficient high specific impulse engine to rocket the system to GEO. This increases the required number of launches. The second scenario is to launch propellant for an engine (say an ion engine) and then beam the power up to the system from 3 or more power beaming stations floating on the Earth's oceans. These stations will eventually converge on the ground point and be used to power climbers up the ribbon. The second scenario will require fewer launches and will prove the capabilities of the power beaming system.

Once the system is at GEO over the ground station, the ribbon can be let out. The end will need a small propulsion system to get the ribbon started toward Earth and to handle the angular momentum change as it descends. A "homing" device on the end will facilitate intercepting the ribbon and affixing it to the ground station. During the spooling out of the ribbon, the deployment spacecraft has risen above GEO so that the center of mass remains at or very near GEO. The spacecraft also must thrust to stay above the ground point because of the angular momentum change at different altitudes. Once the ribbon is completely deployed the spacecraft acts as the counterweight.

The pilot ribbon has a lifetime of only a few years because of impacts from small debris that cannot be actively avoided. Therefore, immediately, climbers must be sent up the ribbon to attach more ribbon to the SE. These climbers must be engineered for the small capacity of the pilot ribbon. As the ribbon capacity increases, the climbers will be larger and will carry more ribbon. After two years, a meter-wide ribbon rated at 20 tons (extra tension in the ribbon) would be completed. Subsequent, higher capacity SEs will be built with an existing SE in much less time, possibly 5 months. Indeed, each elevator's first task may be to build a successor ribbon thus building the SE infrastructure.

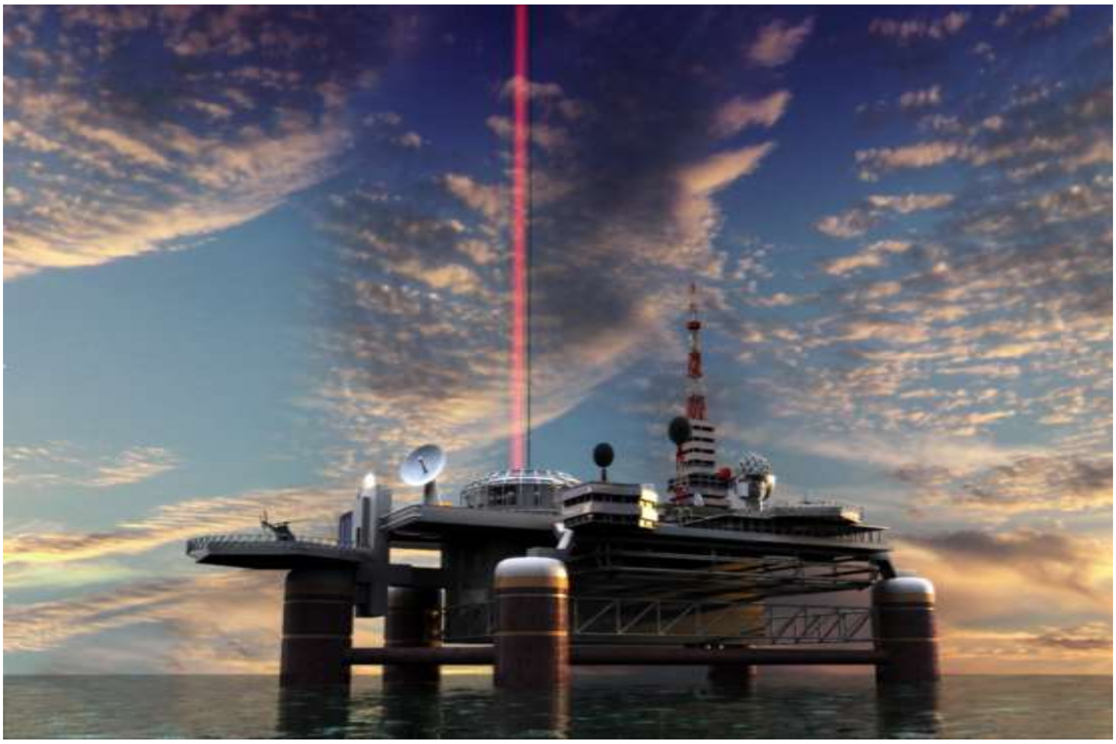

Figure 2 An artist's conception of the Space Elevator's Earthport

4 CHALLENGES

Even if the ribbon and deployment spacecraft were ready to go, there exist issues that must be dealt with before the SE can be deployed. These issues include the technologies required to ascend the ribbon, hazards to the ribbon and the problem of humans traveling on the SE above LEO.

Climbers that ascend the ribbon must operate over a wide range of environments, possess high reliability and climb the ribbon without damaging it. Climbers are assembled, loaded and launched on Earth at the bottom of the troposphere. Within the troposphere weather can be dangerous to climbers especially lightning. The regions encountered during ascent above the troposphere include the stratosphere, ionosphere, and magnetosphere. The atmospheric pressure decreases while the temperature and composition change dramatically as the altitude increases. The stratosphere extends from about 15 km up to about 55 km, the temperature increases from -51C to -15C. The ionosphere begins around 60 km and end around 1000 km. Solar radiation has ionized the atoms in this part of the atmosphere and so the climber must climb through a plasma, albeit a very tenuous plasma. The magnetosphere extends above the ionosphere far out into space. It is a very hard vacuum with very tenuous ions streaming through it. Earth's magnetic field and the solar wind effect its overall shape and boundaries by their effect on the ions. The climbers must operate in all these environments including the radiation environment of the magnetosphere. Climbers must be reliable enough to make at least one 100,000 km trip if not a round trip. A stranded climber could compromise the use of the SE.

Climbers also must have a wide range of uses and so will differ in design. Most climbers will carry and launch payloads. Others will carry out diagnostic measurements, repair tasks, ribbon laying, science experiments and rescue of stranded climbers.

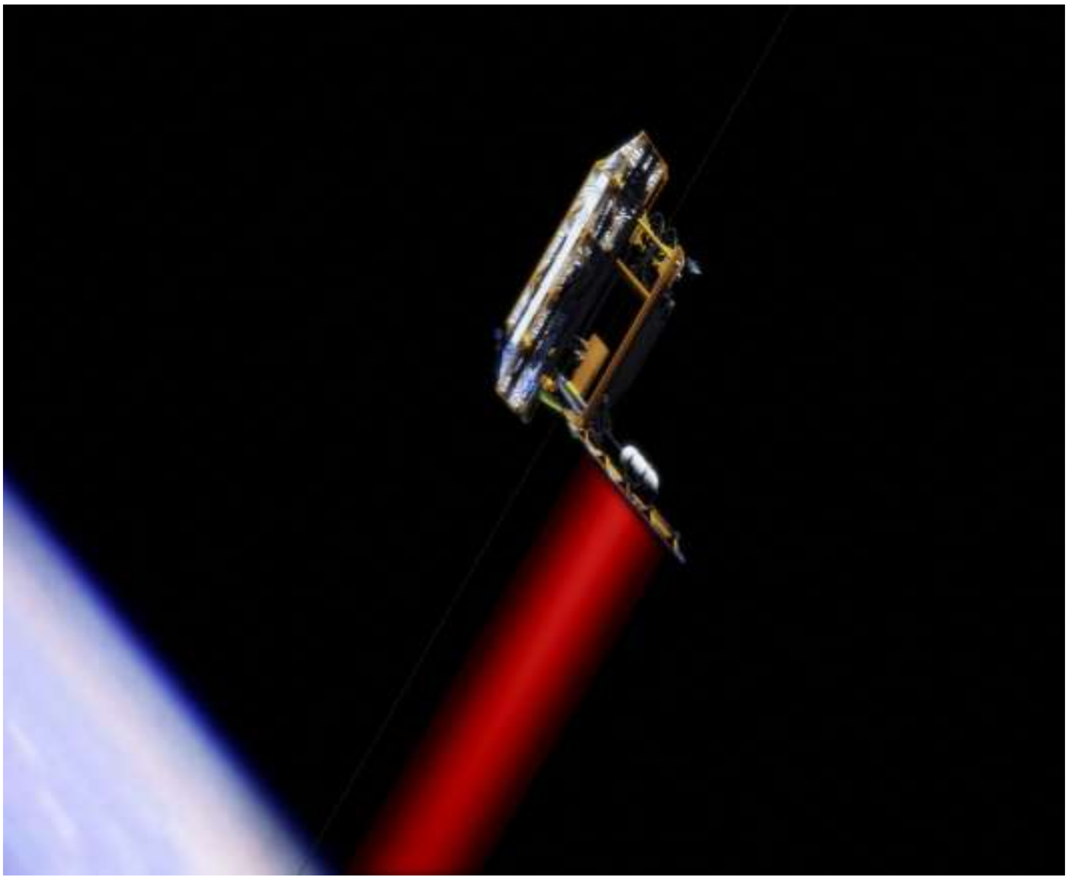

Figure 3 An artist's conception of the Space Elevator Climber ascending the ribbon near Earth and illustrating the power beaming to photovoltaic cells.

The power beaming system that will energize the climbers has three major system components: the infrared laser, the large (~12 meter) telescope and the adaptive optics system. Each of these components (or a close example) exists separately but has never been integrated and operated as a system. An adaptive optics system is required to focus the energy onto the climber photocells through the atmosphere. Current adaptive optics systems are not capable of phasing the entire aperture of large telescopes, but active, closed loop adaptive optics should achieve large aperture phasing.

Hazards to the SE include winds, lightning and aircraft in the troposphere, atomic oxygen in the upper atmosphere, and radiation, solar storms, orbital debris, orbiting satellites and meteorites in the magnetosphere. Placing the ground station on the equator in a region with few storms and defending a no-fly zone around the SE mitigate the troposphere hazards. Coating the SE ribbon with a metal such as nickel or aluminum would protect it from atomic oxygen in the upper atmosphere.

At LEO, space satellites and debris greater in size than 10cm can be avoided by moving the lower end of the elevator. Therefore, the ground station may be a ship or navigable floating platform. The width of the ribbon (1 meter) and its curved cross-section allow the SE to survive micro-meteor and small debris collisions. The statistical rarity of large meteors renders this hazard a low probability. The CNT ribbon is carbon and so is robust to most proton and electron radiation so the damage sustained should be manageable.

The climbers are envisioned to travel at about 200 km/hr. This means that the climbers spend a significant amount of time in the Van Allen radiation belts. The lower belt is mainly trapped energetic protons and the outer belt is primarily energetic electrons. Humans riding on the elevator spend so much time in the radiation belt that the radiation dose is beyond the safe level. Therefore, mitigation techniques must be developed or climbers must significantly increase in speed before humans ride the elevator beyond LEO.

5 SPACE ELEVATOR RIBBON DYNAMICS

Another hazard is the dynamics of the ribbon. This topic is of special interest to the Lift Symposium community so it was extracted from the Challenges section above and discussed here.

SE oscillations can be induced by winds, moving the ground station, the gravitational attraction of the sun and moon, solar storms, solar wind pressure, magnetospheric electromagnetic interactions, thermal heating/cooling and climbers operating on the ribbon.

The ribbon will need to be stabilized by active damping from the counterweight, base and possibly at GEO. Such active damping requires measurement of the oscillations and the appropriate application of impulses to cancel the oscillation. Accomplishing this implies a system that understands the perturbing forces and the evolution of the resulting oscillations as they propagate along the ribbon.

The portion of the Lift Symposium community that carries out dynamic analyses for elevator cables or other slender structures could fill a void in SE research by modeling the elevator cable dynamics realistically. This model would include the following, without knowing the specific properties of the ribbon material:

1. A ribbon with a changing cross section (and so changing mass/length).
2. A ribbon in which the gravitational force changes across its length.
3. A ribbon rotating with Earth by one end being attached to Earth's surface.
4. A ribbon with the other end experiencing a small restoring force in an otherwise free boundary condition.
5. A ribbon experiencing multiple perturbations along its length.
6. Sufficient resolution to model the local effects of a climber operating on the ribbon.
7. A large-scale perturbation such as a solar storm inducing a changing Lorentz force along the part of the ribbon in the magnetosphere.
8. An inelastic collision with an object.

This calculation has never been attempted, let alone approached in sophistication, by previous researchers. There is a great deal of insight to be gained by such calculations. The material properties of the ribbon could be "parameterized" so that as high strength material technology advances, the calculation could be re-run with superior material inputs until the actual ribbon material is fabricated and its properties measured.

6 SPACE ELEVATOR DESIGN VARIATIONS

Colleagues in the Space Elevator community have developed ideas about variations in Space Elevator design. Some of these involve historical variations like elevators with multiple ribbons connecting to Earth and joining into one cable at some altitude, and the free-flying skyhook orbiting Earth.

Other variations involve an adaption of the launch loop invented by Keith Lofstrom and called High Stage One. A very high-altitude platform (~80 km) serves as the starting point of the elevator ribbon thereby eliminating the hazards of the troposphere. A variation that uses similar technology to suspend the climber launch platform is the Multi-Stage Space Elevator.

Other researchers are defining the systems level view of the Space Elevator Transportation System by defining the operations and requirements of the parts of the overall system. Parts of the system include the Apex Anchor, GEO Node and Earthport.

The International Space Elevator Consortium (ISEC) holds a conference every year and has developed many study reports in which these designs are documented. One can join ISEC by going to www.isec.org. The website also has information on the ISEC Reports and other Space Elevator resources.

7 CONTROVERSIAL CARBON NANOTUBE COMMENTS

Years ago, the author of this paper left the Los Alamos National Laboratory to research CNT growth. The reason was that the progress in the field to grow long, strong CNTs appeared glacially slow.

The author attended a conference presentation by Dr. Benji Maruyama of the Air Force Research Laboratory. In his presentation, Dr. Maruyama described the limits of using the chemical vapor deposition (CVD) method to grow CNTs. His team found that the CNT growth was stopped and the CNTs were damaged for the following reasons:

1. The catalyst particles from which CNTs grow become coated with amorphous carbon thereby shutting off the path for free carbon atoms to become a part of a growing CNT,
2. The catalyst particles diffuse into the substrate thereby becoming too small to support CNT growth,
3. Ostwald ripening operates on the catalyst particles increasing the size of the larger ones and decreasing the size of the smaller ones thereby rendering both of the wrong size to grow CNTs,
4. CNTs are damaged by reactions with the hot carbon-bearing gases present in typical CVD growth.

The widespread use of the CVD method in the field is why progress to grow CNTs has been glacially slow. Consequently, traditional CVD is probably a dead end. Since the discovery of CNTs in 1991, the world has poured around $35 billion into CNT research and has only an approximately $700 million annual industry to show for it!

The author spent two years of part-time work developing seven novel synthesis (growth) processes. The first six were defeated by deeper study. Proof-of-principle experiments were carried out on the seventh process, and robust growth of CNTs was achieved. Currently, money is being raised to continue to develop the technology into a process capable of industrialization. If successful, then the promise of this technology will be realized.

The promise of this technology is continuous growth of CNTs that possess pristine molecular structure – exactly what is needed to create a materials revolution on Earth. Once the technology has been developed into myriad products that change our civilization, the Space Elevator will be built as the bouquet of the technology.

8 THE PROMISE OF THE SPACE ELEVATOR

The low cost of access to space promised by the Space Elevator (SE) will enable the exploitation of space. Currently, commercial space business is only profitable in the case of communications. With lower cost to space, many types of commerce will be profitable. Solar power satellites that beam power to Earth will provide clean, inexpensive electrical power. Earth observation and scientific space missions will be expanded in number and capability. Human and robotic exploration as well as colonization will be possible at much lower cost. SEs could be thrown to the moon and Mars and deployed to enable the suppling of settlements and two-way trade.

Space tourism, bolstered by the success of the Ansari X-Prize winning Space Ship One (the first private reusable manned spacecraft to reach space twice within two weeks) will be stimulated by the SE as well. Humans will ride to LEO at first, returning either back down the elevator or by dropping off the elevator and re-entering the atmosphere. Eventually humans will vacation at the GEO station or depart from the elevator to other parts of the solar system.

In conclusion, the Space Elevator will open up space and its resources to help mankind solve its problems here on Earth and to expand into the solar system. What could be better than to work on this project? After all, now that the history of the 20th century is being written, it is clear that one of the greatest achievements was that humans landed men on the moon and returned them safely to Earth. When they write the history of the 21st century, they will say that one of the greatest achievements was the building of the Space Elevator!

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BIOGRAPHICAL DETAILS

Dr. Laubscher is a PhD in Physics with a concentration in Astrophysics. During his career at the Los Alamos National Laboratory that included R&D of astronomy projects, space mission design and system engineering, space particle instrumentation, remote sensing technologies, novel electrodynamic detection techniques and biometrics, Bryan became interested in the Space Elevator.

Pursuing the R&D of the Space Elevator has led him to start Odysseus Technologies, Inc, a small company based in Washington state with the goal of developing high strength carbon nanotube materials. Odysseus Technologies has invented a new way to synthesize carbon nanotubes and completed proof-of-principle experiments. Now the company is pursuing technology development and plans commercialization in the near future.

Bryan's current non-profit Space Elevator activities include being on the Board of Directors of the International Space Elevator Consortium and presenting the Space Elevator presentations at various venues.

Bryan now lives in Olympia, WA with his wife Carla.

Traffic Analysis for a Multi Car Lift System Used as Local Group

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Keywords: multi car lift system, elevator, traffic analysis, handling capacity, quality of service, departure delay, Monte Carlo simulation

Abstract. In a circulating multi car lift system, multiple lift cars are sharing shafts. Shafts are used as one way tracks and cars are changing between shafts horizontally. Handling capacity depends on the time between two subsequent cars (multi car cycle time). If these transportation systems are used in buildings as local groups, people's individual destinations lead to different stops of cars. That affects the average multi car cycle time.

This paper explores the average multi car cycle time in a pure incoming traffic situation of a multi car lift systems used as local group considering quality of service constraints. The traffic analysis is established by applying Monte Carlo simulation that calculates an additional multi car cycle time avoiding "traffic jams". Based on a simplified calculation model handling capacity results are presented for different numbers of served floors and different numbers of passengers per car. Results are affected by floor to floor distances and required distances between cars.

1 INTRODUCTION

1.1 Circulating multi car lift system

In a circulating multi car lift system (MCLS) multiple lift cars are sharing the same shafts. This kind of lift system has been widely considered [1, 2, 3, 4]. Vertical shafts are used as one way tracks – one in the up direction, another in the down direction (see Figure 1). Cars do not have ropes and are propelled by linear motors. The lift cars can move vertically and horizontally. Exchanger units enable change in the orientation of car movement between vertical and horizontal [5]. A preferred case of application for a circulating MCLS is connecting entrance lobbies with sky/transfer lobbies as shuttle lifts [6]. But a circulating MCLS is not limited to shuttle applications. It can also be used for a local lift group to distribute passengers to their final destination floors [7]. Accepted rules of lift behaviour [8, 9, 10, 11] are applied also to MCLSs. Additional rules [7] need to be considered to reduce departure delays [12] caused by "traffic jams". Departure delays are caused by different number of stops and different stops for different cars.

Cycle time: The multi car cycle time (t_{cy}) is the time between two subsequent cars e.g. departing from the main entrance floor from the same shaft door [6]. There is a minimum possible cycle time depending on stopping and exchanger times of cars.

Delaying stops: Stops of a leading car can block the shaft and delay the processing of a following car stop sequence. Figure 2 shows a general example of a spatial plot of the positions of two subsequent cars. $D1(t)$ is the position of the leading car and $D2x(t)$ is the position of the following car. The leading car 1 ($D1(t)$) has one "delaying stop" that causes a safety distance violation (or a "traffic jam") if car 2 ($D2x(t)$) departs from the bottom landing after a minimum possible cycle time (t_{cy}). A longer cycle time between cars can avoid these "traffic jams" of lift cars. The following car arrives later at the main entrance floor. Therefore, an additional time needs to be added to the minimum possible cycle time. The additional time between two subsequent cars avoiding any "traffic jams" for the following car in an up direction shaft depends on the stop sequence of the leading car and the following car.

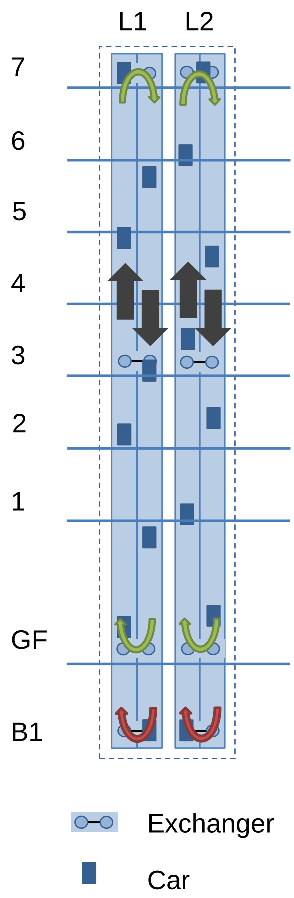

Figure 1 MCLS as local group

An additional cycle time delay (t_{CyD}) for the following car 2 ($D2(t)$) results in a longer cycle time at the main entrance floor and avoids the safety distance violation (see Figure 3). “Delaying stops” need to be calculated to derive the additional cycle time. Both stopping sequences (the leading car stopping sequence and the following stopping car sequence) need to be analysed and compared.

The cycle time delay (delayed departure) can be determined if the following car has a later arrival at the bottom landing. Another option is that the following car has a delayed door opening for loading passengers. A later arrival or a delayed door opening at the bottom floor does not affect any passengers inside the cabin as the cabin always arrives empty. That increases the waiting time (WT) for passengers but reduces experienced departure delays inside the cabin. Waiting for a lift to arrive is an expected scenario for passengers in opposite to departure delays. The delayed door opening should only be applied if passengers are not aware of a car already waiting behind the shaft door. An additional cycle time can be reduced if flexible speed patterns are used (e.g. starting early with a reduced velocity). Adaption of the speed pattern is not considered in this paper’s analysis.

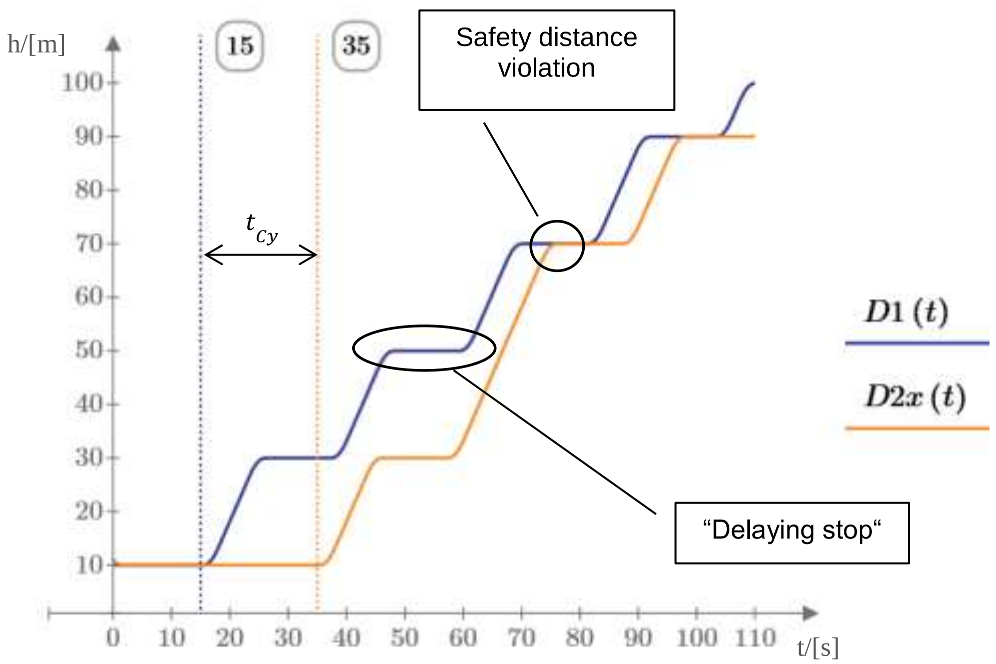

Figure 2 Spatial plot indicating a delaying stop

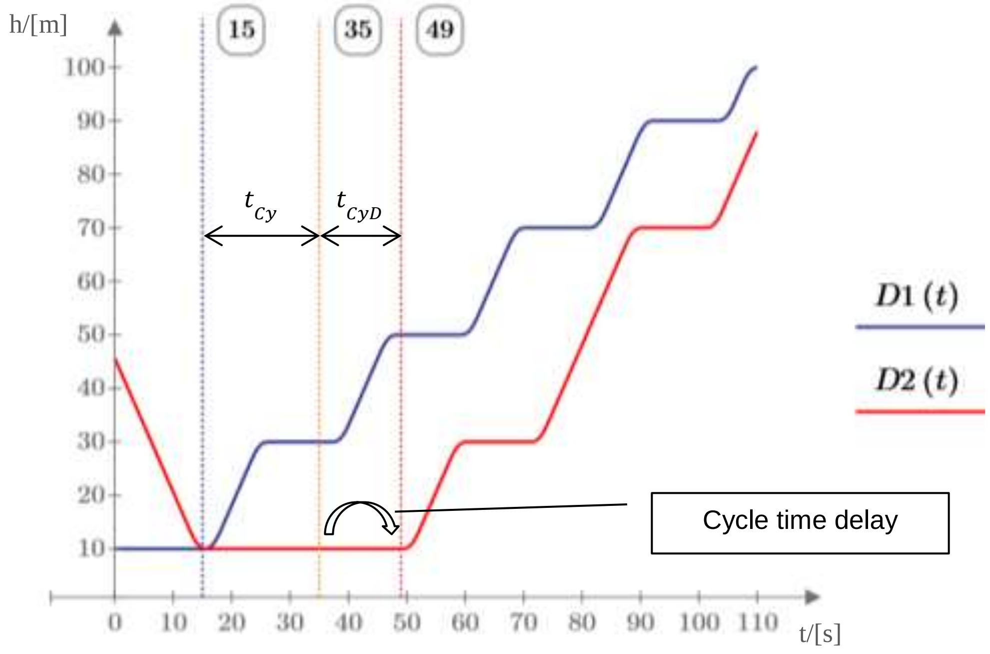

Figure 3 Spatial plot with an additional cycle time delay

1.2 Analysis methods

Lift traffic analysis is the "determination of statistical characteristics of passenger movements in an elevator […] system" [13]. In lift traffic design and analysis, different methods exist and are used. In general there are two categories: calculation and simulation [14].

1.2.1 Analytical method (calculation)

The classical method is an analytical, equation-based calculation – the round trip time (RTT) calculation [9, 13]. The RTT calculation is based on pure up peak traffic conditions. Based on several inputs (lift configuration and operation in a building) the average up peak interval of lifts departing from the main terminal floor is calculated. The RTT calculation has limitations as it is based on assumptions and simplifications. Modifications of the classical RTT calculation are necessary to address limitations analytically. These can be complex and especially combinations of addressed limitations become complicated [15]. Extensions to the classical RTT calculations overcome limitations [16]. The analytical method also does not consider individual dispatching and control algorithms of the lift system.

1.2.2 Simulation method (event based)

Lift traffic simulations are discrete event based or time-slice (timer-event-based) simulations. The whole process of passenger arrivals and transportation in lift cars is simulated including the lift functionality. As traffic simulation is closer to "real life" it has some advantages compared to RTT calculations [13]: it models the lift control system; it enables more realistic passenger arrivals rather than constant passenger arrival like assumed in the RTT calculation and it enables various types of results that can be analysed. The passenger waiting and transit time results are the main measure for quality of service, but other analysis is possible. Traffic simulation covers different kind of building configurations, traffic types, lift configurations and types of lifts systems. But lift traffic simulations are more complex and time consuming compared to analytical calculations [17, 18]. If a traffic simulation is configured according to the assumptions of a RTT calculation it can be shown that results are consistent [17]. ELEVATE is a lift traffic simulation software [19] that is widely used in the lift industry for traffic design and analysis. It enables the connection of proprietary dispatchers for known roped lift systems [20]. It was shown that simulation results are consistent with real world results [21].

1.2.3 "Mixed" method (Monte Carlo simulation)

A kind of a "mixed" traffic design method uses the Monte Carlo simulation method to evaluate the RTT of a lift in up peak traffic condition [15]. If the building configuration becomes complicated it helps to overcome combinations of the mentioned limitations of the RTT calculation method. A random passenger generator generates the passenger's destinations for each round trip. The probability of the destination floors is based on the building population for each floor. To cover multiple entrance floors the arrival floor of the passengers is also generated based on the arrival probability for each entrance floor. A round trip calculator calculates each RTT. It uses a kinematic calculator to consider unequal floor heights and trips where the rated velocity is not reached. If the number of samples is 1000 it was shown that the accuracy of the results is <+/- 0.3% [22]. This is a good method if equations for the analytical calculation become complex.

2 MCLS AS LOCAL GROUP

2.1 Cycle time in local MCLS groups

To calculate the incoming handling capacity (HC) the average cycle time of a local circulating MCLS needs to be determined considering existing constraints like safety distance and avoiding departure delays/"traffic jams". The stop sequence in an up direction shaft of a leading car can be compared with the stop sequence of a following car. The number of delaying stops indicates an additional cycle time delay. Each following car is the leading car for the next following car. With the use of a Monte Carlo simulation multiple samples of leading and following car stop sequence comparisons can be made.

2.1.1 Additional cycle time delay

There is a necessary cycle time delay for each delaying stop. This additional delay depends on "time consumed when making a stop" [23] for intermediate stops. This includes the time for standing at the floor itself but also includes the longer time for acceleration and deceleration compared to the time passing the same distance with rated velocity. The standing time includes passenger transfer times and door times. For simplicity in this analysis the time consumed for each intermediate stop is calculated with the same duration of time although the number of transferring passengers may be different for each stop. For each delaying stop the cycle time needs to be delayed by the time consumed for a stop.

2.1.2 Stopping sequences and safe floors

Depending on passengers' destinations and assigned calls every lift car in a MCLS has an ordered sequence of stops at landings in the up direction shaft. For all cars the first stop needs to be the bottom landing. This stop at bottom landing is for passenger loading at the main entrance floor. The last stop must be the top landing of the up direction shaft. This top landing stop is necessary for the horizontal shaft changing of a car using the exchanger unit. It is expected and likely that there is no additional delay for the horizontal movement at the top floor. It can also be used for passenger unloading. There may be additional stops/floors between the bottom and the top floor.

It is also important to know the floors the following car is able to stop at depending on the leading car stops and required distance constraints. Depending on required distances and distances between floors a following car can stop directly below the leading car stop floor at the same time or, more likely, one floor needs to be in between the leading and following car stops. From the leading car stops sequence a safe floor sequence for the following car can be derived.

2.1.3 Comparison of stop sequences

There is at least the minimum possible cycle time between the first stop of the leading car and the first stop of the following car (the first stop is the bottom floor). To calculate the delaying stops a stop of the following car needs to be compared with the safe floor for the following car belonging to/derived from the leading car's stop ahead. The movement and all stops in the whole up direction shaft needs to be analysed and delaying stops can be counted and calculated.

2.1.4 Simulation/Calculation

The average cycle time for a local MCLS is expected to be higher than the minimum possible cycle time if "traffic jams" shall be avoided. To calculate an average cycle time in a pure incoming traffic the stopping sequences of multiple subsequent cars need to be compared. The stopping sequences of the cars are depending on the passengers destinations. To calculate the average cycle time of multiple subsequent cars the method of Monte Carlo simulation is used. This method was introduced to evaluate the round trip time (RTT) of conventional single car lift systems in pure incoming situations (see section 1.2.3). To evaluate the average cycle time in local circulating MCLSs the general structure is shown in Figure 4.

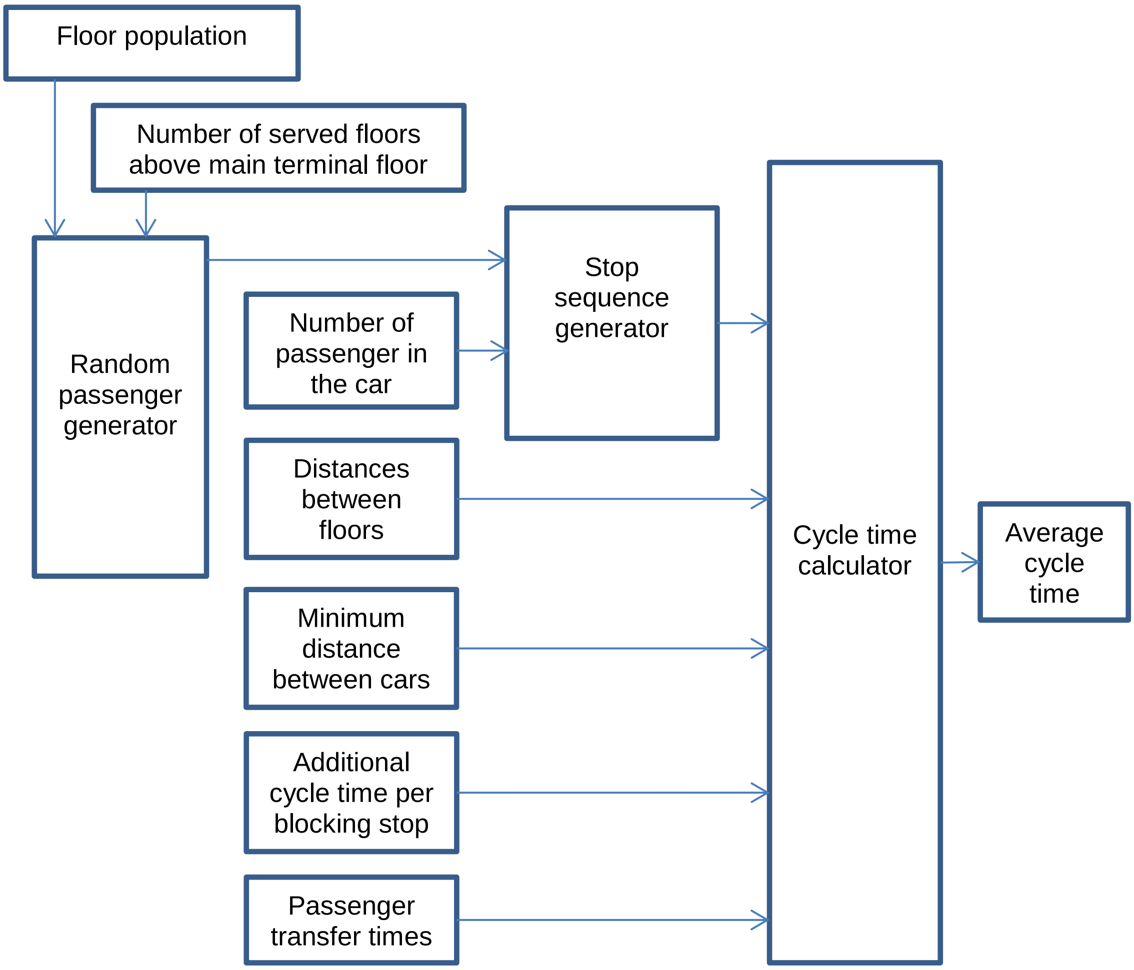

Figure 4 Structure of the Monte Carlo simulation to calculate the average cycle time

Random passenger generator: The file output of the passenger generator from the lift traffic simulation software ELEVATE [19] is used to generate an ordered passenger list with an arrival floor and a destination floor for each passenger. As input the number of floors and the floor population is necessary. The same population on each floor and a traffic mix of 100/0/0 for “in/out/interfloor” is used.

Stop sequence generator: The stop sequence generator assigns passengers from the ordered list to the next arriving lift car. Every car is filled up to the number of passengers fitting into the car. Depending on the destinations of the passengers in the car a stop sequence of the car is generated. A stop at the top floor is mandatory as it is used to move the lift car horizontally to the down direction shaft.

Cycle time calculator: The cycle time calculator comparing the stop sequences of a leading and a following car. Two subsequent cars are analysed and delaying stops are calculated avoiding departure delays and “traffic jams”. A cycle time for the following car is calculated (minimum possible cycle time + additional cycle time delay). Input parameters for the cycle time calculator are distances between floors, minimum distances between cars, additional cycle time per blocking stop and passenger transfer times. The cycle times of multiple subsequent result in an average cycle time. An average pure incoming HC can be calculated.

2.2 Results

2.2.1 $d_{min} < d_{f2f}$

The average incoming HC derived from the average cycle time depends on the number of passengers per car and the number of served floors above the main entrance level. In case the minimum distance between cars is shorter than the floor to floor distances ($d_{min} < d_{f2f}$) the results depend on the number of passengers per car is shown in Figure 5. The diagram shows the results of one MCLS loop serving all calls in a 100% incoming traffic situation. If the number of served floors increases the probability of different stop sequences increases and therefore the probability of delaying stops increases. But there is a minimum HC. If number of served floors is high, the impact of additional served floors is less.

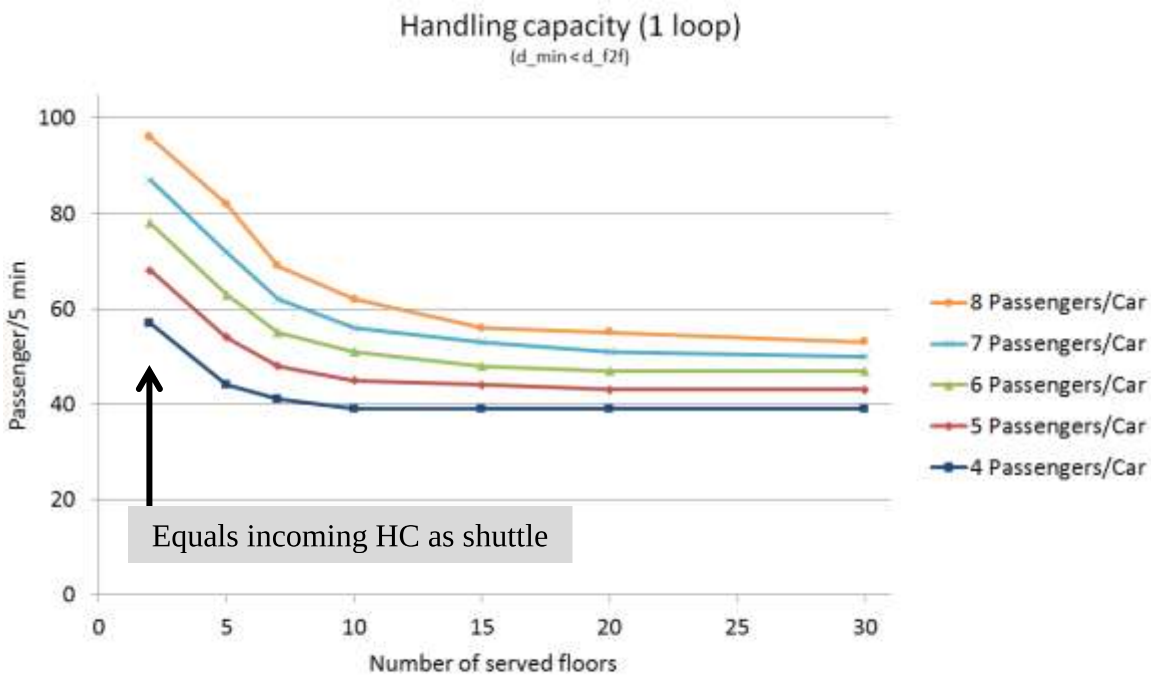

Figure 5 Average incoming HC5 for one local circulating MCLS loop

2.2.2 $d_{f2f} < d_{min} < 2\ d_{f2f}$

It is very likely that the minimum distance between cars is longer than the floor to floor distances ($d_{min} > d_{f2f}$). HC will be affected if a following car has to stand at least two floors below a stopped leading car ($d_{f2f} < d_{min} <\ 2\ d_{f2f}$). Figure 6 compares the results with 8 passengers per car with two cars able to stand next to each other ($d_{min} < d_{f2f}$) and an additional floor required between two stopped cars ($d_{f2f} < d_{min} < 2\ d_{f2f}$). It is assumed that the distance from the main entrance floor to the floor above is longer than the minimum distance. This is a reasonable assumption because main entrance floors are often high.

The additional safety distance constraints reduce the HC. If a leading car is standing at a floor it also blocks the landing below. If the lift system serves a low number of floors the negative effect is higher than serving more floors.

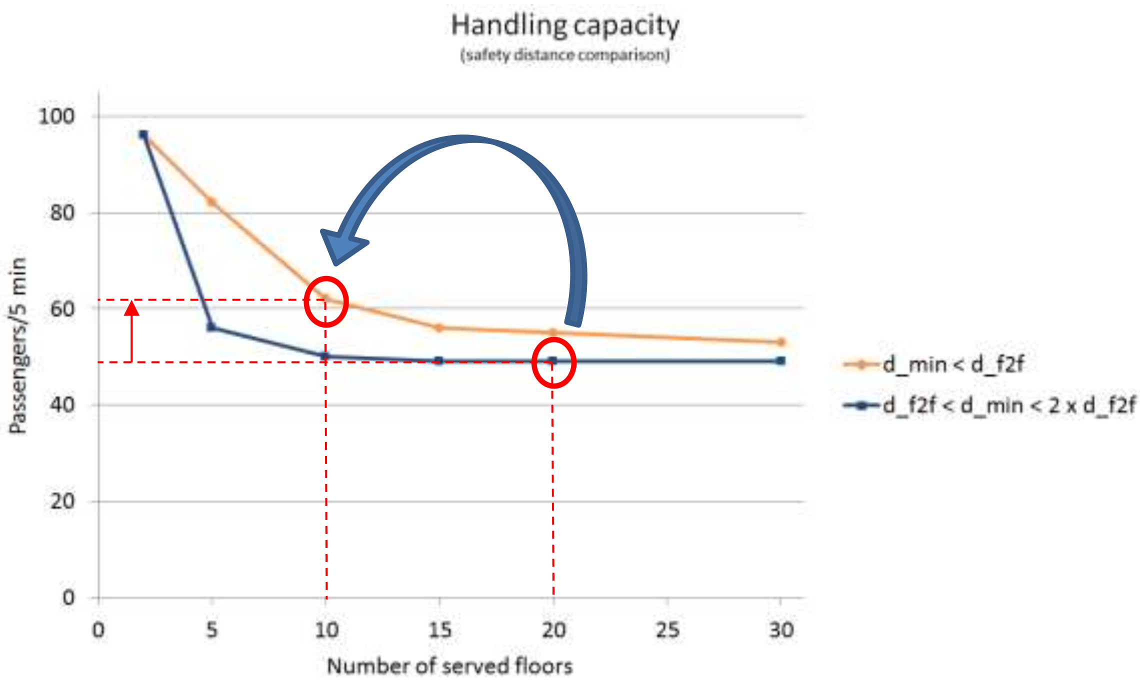

Figure 6 HC depending on the safety distance constraints

“Served floor assignment”: In a group of two circulating MCLS the served floors from the main entrance lobby can be split between loops in an alternating manner similar to interleaved zones [9] (see Figure 7). This reduces served floors per MCLS loop and increases the distance between served floors. Therefore, the HC5 can be increased (see Figure 6).

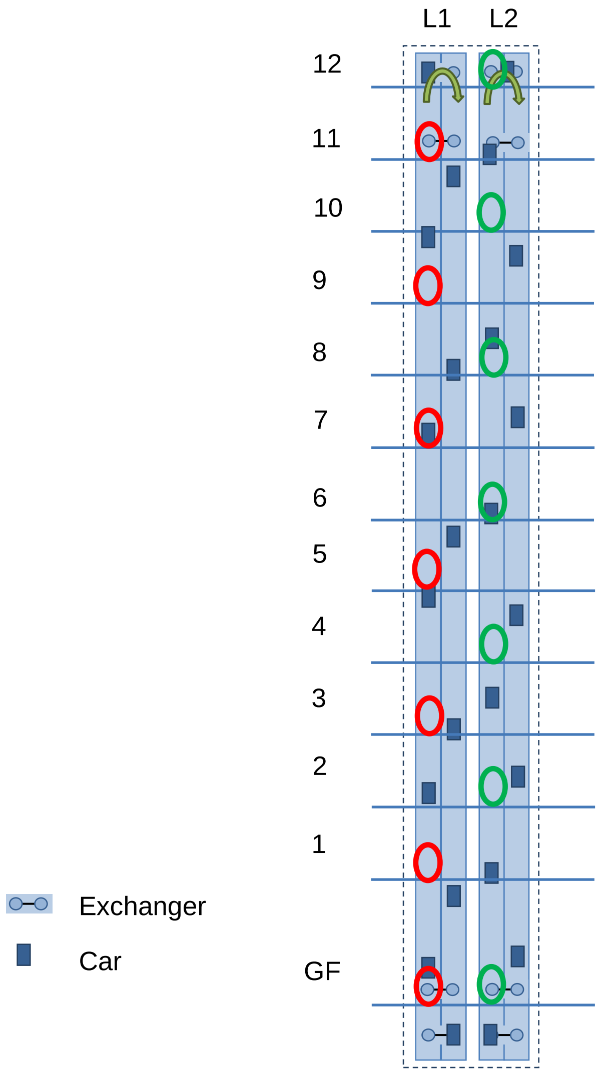

Figure 7 Alternating floor assignment of multiple MCLS loops

3 CONCLUSION

This paper introduces traffic analysis for a circulating MCLS used as local group. Based on a simplified additional cycle time calculation the HC for a 100% incoming traffic is calculated avoiding “traffic jams”. The Monte Carlo Simulation method is used. The result for different numbers of served floors and different numbers of passengers per car were calculated. In case of a higher number of served floors the probability of a different number of stops increases and the cycle time needs to be increased to avoid “traffic jams”. If more than about 15 floors are served, it is not needed to increase the cycle time further. An increased cycle time reduces HC compared to a shuttle application. Furthermore, safety distance and distance between served floors affects results. If cars cannot stand next to each other at two adjacent floors the HC is further reduced.

If multiple MCLS loops are operated as a common lift group, the performance of each loop can be improved with destination control or “served floor assignment” (compare with sub zoning for conventional lifts) because the operation of each MCLS loop can be optimised.

Full traffic simulation including control algorithms are needed to prove the results. Control algorithms need to provide expected system behaviour. Interfloor traffic may affect the minimum possible cycle time if “traffic jams” shall be avoided. Interfloor traffic may cause additional stops. Additional stops can have a negative effect on calculated delaying stops but also can have a positive effect on calculated delaying stops.

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Transient Dynamic Computation for Mega-High Rise Lifts

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Keywords: lift, vibration, sway, multi-physics, substructures, traffic

Abstract. The megatrend of urbanization brings new challenges for the lift industry; the need for keeping the travel time short may conflict with the demand for safety and comfortable ride. In the case of a mega-high building, the performance of the lift system can be substantially affected by the response of the building to various excitation, such as strong winds.

This paper focuses on the prediction of in-car vibrations for a specific lift configuration with various running parameters in the event of building sway, using a chain of multi-physic computation. The core of the computation is a direct transient dynamic finite element method where user subroutines were developed to accommodate installation accuracy in a range of millimetres for a travel in the range of 500 - 1000 m. Aerodynamic loads were considered by using a transient fluid dynamic computation. Behaviour of ropes while the lift is in motion with different building sway parameters and speed profiles were computed using a finite difference method. The computational results were validated in no-sway conditions and the computational method was used for predicting the in-car behaviour during sway conditions.

The advantage of this approach is that the dynamics of the entire structure can be analysed for every lift component: car, sling, roller, roller's stopper; for the entire travel and for different running parameters. This provides the opportunity of optimizing – for example – the lift speed, based on the targeted ride comfort class and lift system performance in various sway conditions.

Finally, to demonstrate the one possible usage of this calculation method, the results of the multi-physic computation were combined with traffic analysis and the probability of various excitations to assess the long-term implication to the lift system performance.

As a result, an enhanced sway operation of the elevator was developed, for which an optimized car speed profile was proposed instead of traditional high wind mode. Although no major improvement of handling capacity on a yearly level could be noticed, the service provided to lift users for highly windy days, will not go unnoticed.

1 INTRODUCTION

The demand for taller buildings creates the challenge of how to ensure outstanding ride comfort of lifts in severe environmental conditions like building sway. To respond to this challenge the lift manufacturers have been forced to use advanced computational solutions for predicting the dynamic behaviour of the car.

In several articles [1, 2, 3, 4], the dynamics of the ropes in sway conditions were studied and analytical models were developed in order to understand their effect on the lift dynamics. However, studies that focused on the effect of building sway to in-car vibrations were very challenging to find.

The focus of this paper is the computation of in-car vibrations, using a chain of multi-physic computation: transient finite element for mechanical and fluid dynamics, differential equations, data from measurements and statistical methods.

In KONE the development and validation of transient computation for in-car vibration started several years ago [5, 6]. After the confidence in the models reached a certain level, their complexity was extended to cover the impact of building sway on in-car vibrations. The computation enables the optimization of the car velocity as a function of sway amplitude, in order to ensure the quality of the lift service in challenging weather conditions. Finally, the impact of using an optimized speed profile for high wind conditions was computed and compared to traditional lift operational methods.

2 SELECTION OF THE COMPUTATIONAL STRATEGY

The computational strategy was chosen based on the frequency range of interest of in-car vibrations, dictated by human perception. Due to human skeleton, ligaments and other damping mechanisms, while standing, ISO8041:2017 recommends a frequency range under 10 Hz for in-plan vibrations and under 80 Hz for vertical vibrations [7]. Multi-body simulation and finite element method were the most suitable methods for this frequency range, however since the flexibility of the building was the focus of the study, finite element was selected.

The next challenge was the size of the model, which included over 500 meters guide rails with misalignments of fractions of millimeters, sling, car, ropes and travelling cables. To overcome this challenge a substructure modelling technique was chosen, where the model was divided into regions (substructures) for which the stiffness, mass and damping matrices were computed independently and reassembled in the global solution. By using a Guyan reduction [8], the mass and stiffness matrix of the substructure are reduced to several retained nodes that significantly decrease the size of the global model. The drawback is that only linear and small displacement behaviour can be modelled accurately with this method. Therefore, the division of the model has to be carefully selected.

The global model of a double deck lift (Fig. 1) consists of guide rails and fishplates modelled as beam elements with variable profile; brackets, modelled as springs; sling and car substructure (Fig. 2) attached to suspension, compensation rope and travelling cable and guide shoes substructure. With this choice, all the components affecting in-car vibrations were considered and evaluated in the computed solution [6].

The air loads due to counterweight passing by (Fig. 3) were computed using finite element method for fluid dynamics and the pressure variation was applied on the walls of the car, for the time of the counterweight transition.

The guide shoes (Fig. 4) were raising also challenges. The levels controlling the wheels, the springs and the stoppers had large displacements and rotation degrees of freedom; therefore, their linearization into one substructure was decreasing the accuracy of solution. The decision was to divide the guide shoes into several regions: substructure without levers (Fig. 5) three substructure for levers (Fig. 6) and model the three stoppers and three springs at global level. The rubber wheels were assumed to be always in contact with the guide rails with a small friction coefficient and to glide along guide rails instead of rotate.

Even with this solution, where separate regions were solved in parallel, the model was too big to be analyzed in reasonable time. For that reason, instead of modelling the misalignments of the guide rails as a geometry in the model, a user element has been defined for each connection between guide rail shoes and guide rail [6]. Within user element subroutine, the misalignments of the guide rails and the displacement of the building due to sway were prescribed. These values were measured for several guide rails and existing buildings and estimated for new projects.

Finally, the rope forces affecting on the sling were computed using a finite difference method and applied as variable load, depending on the car position in the shaft.

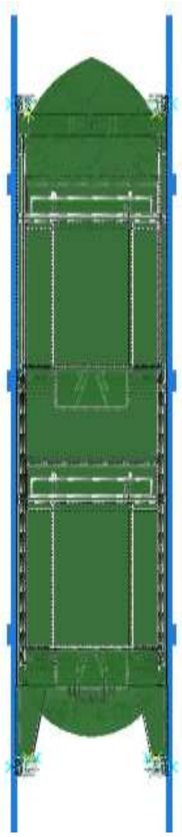

Figure 1 Lift global model

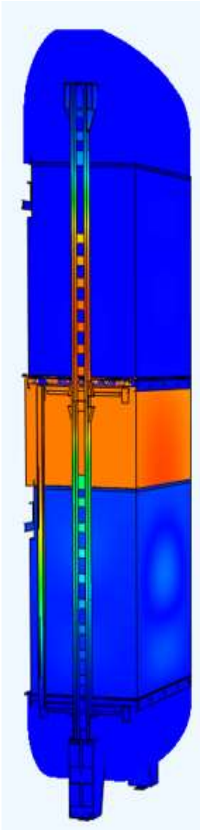

Figure 2 Sling-car substructure

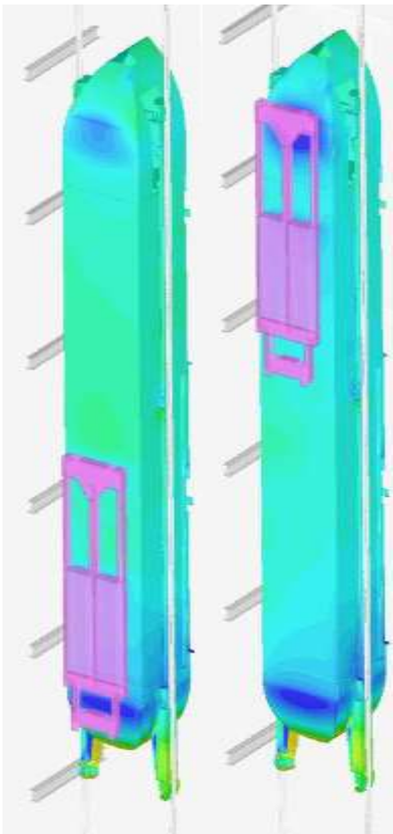

Figure 3 Counterweight impact

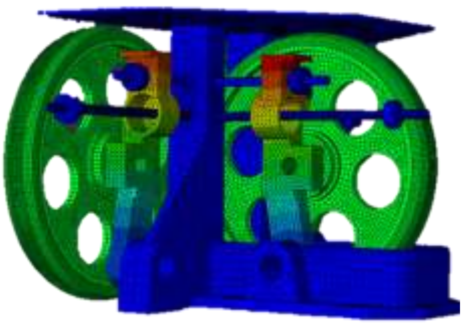

Figure 4 Roller guide shoe

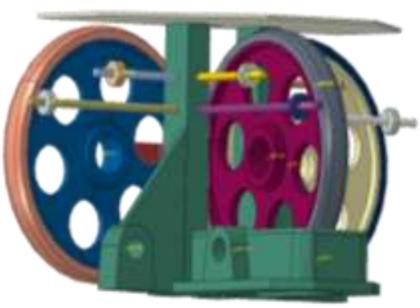

Figure 5 Substructure

Figure 6 Lever

3 LOAD CASES

Several load cases were analysed and compared during this study.

Within the guide shoes substructure, a contact step was applied between wheels and guide rail, followed by an eigenfrequency extraction analysis and the substructure generation.

Within the sling car substructure, a static step containing gravity load, pressure load due to the counterweight passing by was followed by an eigenfrequency extraction and finally the substructure generation.

At global level, the misalignments of the guide rail installation (Fig 7) were applied, using the user element that defines the displacements of the guide shoes rollers. The building sway (Fig. 8) was applied to the brackets fixing the guide rails to the shaft [6].

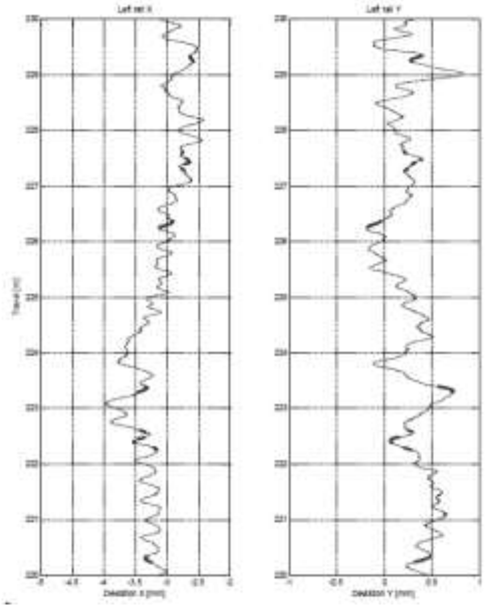

Figure 7 Guide rails misalignments

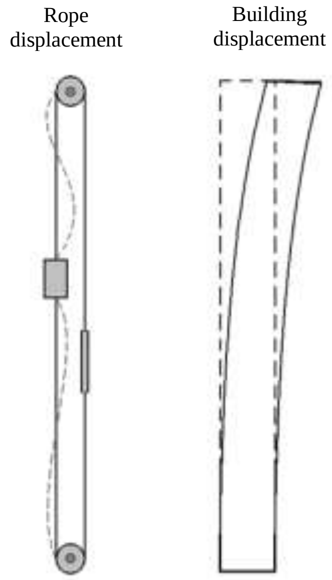

Figure 8 Building sway

The compensating ropes and travelling cable were modeled as user elements where the mass varied with the length of the elements and the suspension and compensating rope forces computed for each velocity profile and sway definition were applied on the sling [6].

The impact of building sway and speed to ride comfort was evaluated using different speed profiles. The in-car vibration had to be analysed as a function of lift speed and building sway and the target was to find the best suitable profile that can ensure a good ride comfort and a minimum travel time.

4 THE EFFECT OF BUILDING SWAY TO LIFT SYSTEM PERFORMANCE

The philosophy of evaluation of the effect of building sway to the lift system performance was adopted from a presentation by Kalliomäki [9]. The specification of the assessed hypothetical lift (group) is given in Table 1. The evaluation was done in three stages: in the first stage the aim was to find a best possible speed profile in sway conditions while maintaining a good level of ride comfort, in the second stage, the effect of these speed profiles on the handling capacity of a lift group was evaluated based on traffic simulations and in the final stage the overall implications of this effect were analysed over a longer period of time by using probability information of different sway magnitudes.

Table 1 Lift parameters

Travel [m]	508	Nominal speed [m/s]	10
Acceleration [m/s^2]	0.8	Start delay [s]	0.7
Jerk [m/s^3]	1.2	Advance door opening distance [m]	0.0
Group size	4	Advance door opening speed [m/s]	0.0
Door opening time [s]	1.5	Passenger transfer time [s]	1.0
Door closing time [s]	3.1	Rated load [passengers]	20
Photocell delay [s]	0.9	Building frequency [Hz]	0.1394

4.1 Speed profile policy selection

In order to evaluate what the impact of building sway and velocity on ride comfort, 19 speed profiles (Fig. 9) for an up-running lift were analyzed for the same sway amplitude of 88mm. Some of the results are presented in Figure 10. For the speed 10m/s speed profile, also the evaluation of sway amplitudes 88mm, 66 mm, 53 mm, 44 mm and no-sway on ride comfort were also done (Fig. 11).

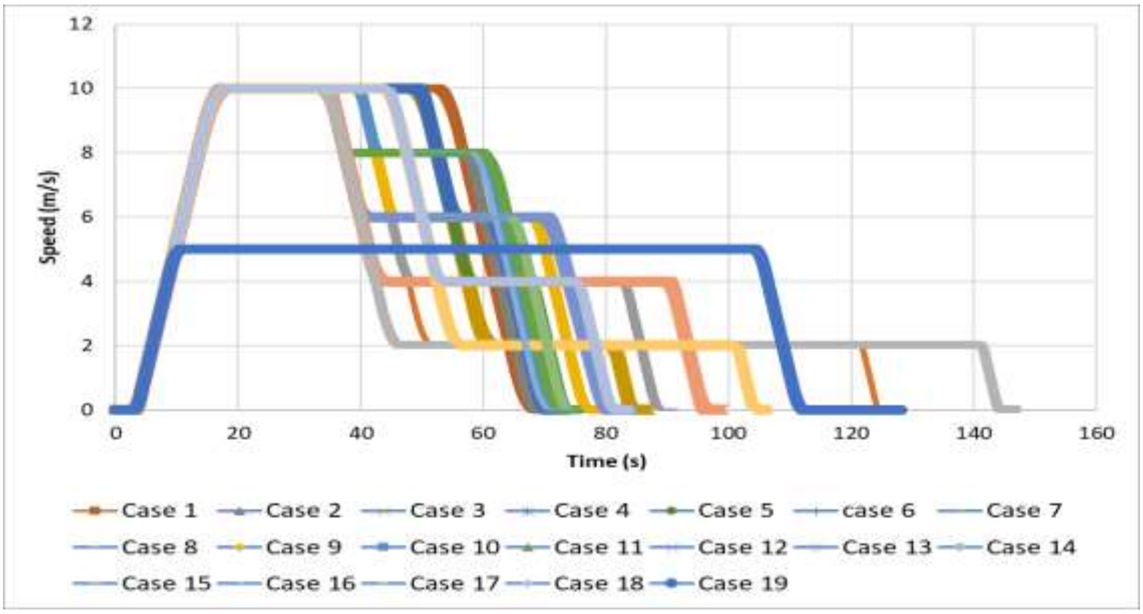

Figure 9 Analyzed speed profiles

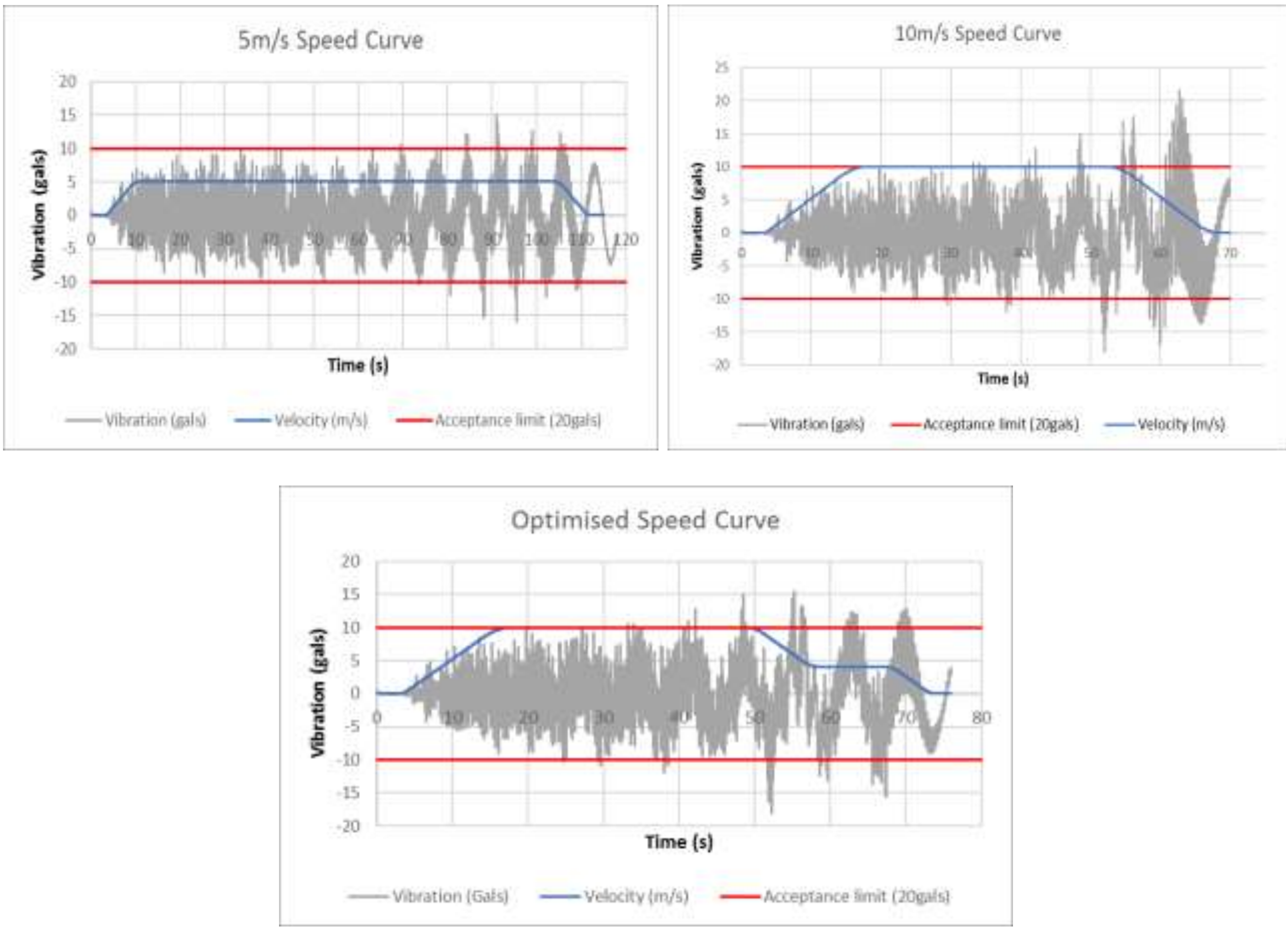

Figure 10 In-car vibrations for different speed profiles

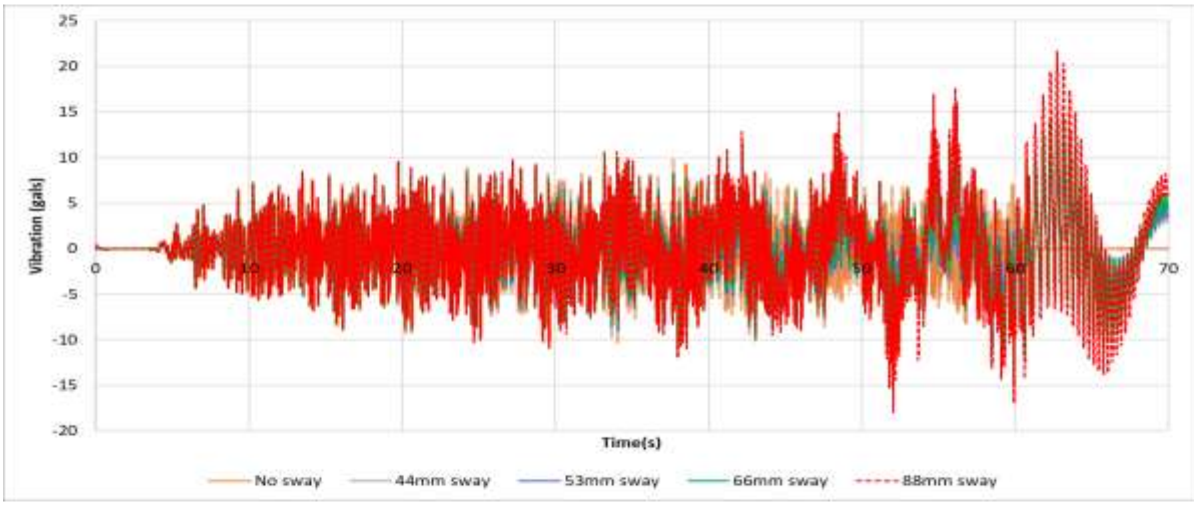

Figure 11 In-car vibration for 10m/s and different building sway amplitudes

For each profile, in-car vibrations were computed and compared against the acceptance criteria, which is – based on KONE ride comfort classes – that the maximum adjacent peak-to-peak magnitude must be under 20 gals.

An analysis of the results indicates (Fig. 11) that only when the car passes the level of 396 m the in-car vibration does not fulfil the acceptance criteria. For the studied case, the optimal solution among considered cases was chosen (Case 16, Fig. 9).

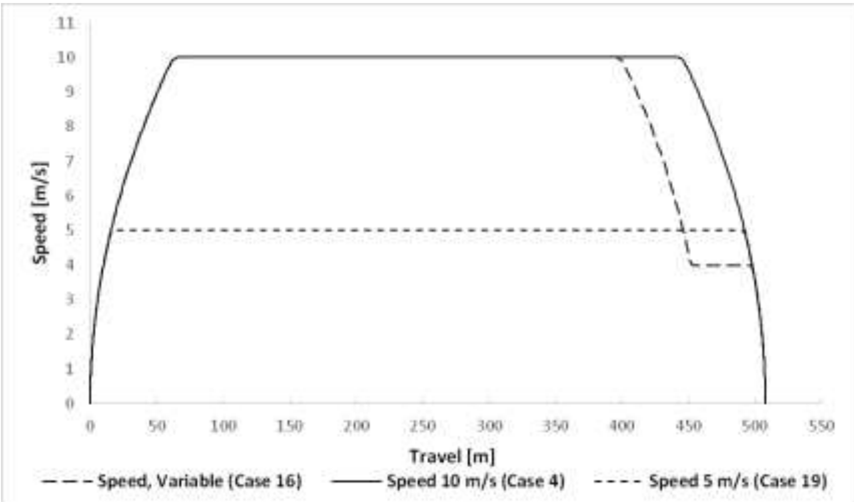

Figure 12 Selected speed profiles

By using 10 m/s profile (Fig. 10), the peak-to-peak car vibration is 28.5 gals, therefore not fulfilling the acceptance criteria. The flight time is 64 s. By using the common solution of reducing the speed to half (5 m/s), the peak-to-peak car vibration is 18.1 gals and the flight time is 109 s. By using the optimised profile (Fig. 12), the car can run with 10 m/s until 396 m and then decelerate to 4 m/s. The peak-to-peak car vibration is 19.7 gals and the flight time is 71s.

Analysing the result (Fig. 11) shows also that ride comfort is always within the acceptable range when the building sway is less than 53 mm. This means that in those conditions the nominal maximum speed of 10 m/s can be used for the whole run, corresponding to less than 20 gals in-car vibrations.

4.2 Effects on handling capacity

This section assesses the impact of different speed strategies applied during a building sway. The impact is measured in terms of handling capacity and waiting time. The former measure is the number of persons the lift group can transport from their origin floors to destinations within a 5-minute period while the latter one is how long passengers need to wait for lifts at lobbies as an average. Two hypothetical lift groups are considered, each consisting of 4 lifts. These lift groups may not satisfy all traffic planning recommendations. Table 1 shows the lift parameter values used in both groups.

In the first group, denoted by Group A, all four lifts are shuttle lifts and they serve only the main entrance level, 0, and the observation deck located at the top of the building at level 508 meters. The second group, Group B, serves the main entrance level and the 20 highest floors. Table 3 gives the building parameters. Population per served floor is assumed to be equal.

For both groups, three different speed profile policies are used. In the first policy, denoted by P10, speed profile for any run is an ideal speed profile with the maximum velocity of 10 m/s (if the maximum velocity is reached), and this policy is used during calm weather. For detailed information about ideal lift kinematics the reader is referred to Peters' study [10]. The second policy, P5, is the same as the first one, except the maximum velocity, which is now restricted to 5 m/s. This policy represents the current practice used during high wind in which the maximum velocity is dropped to half.

In the last policy, PE, speed profile for any floor pair is an ideal speed profile with the maximum velocity of 10 m/s except runs from the main entrance level to upper floors. For those runs the speed profile is formed according to local optimal speed profile for a 508 meter run where the first deceleration to speed 4 m/s starts at level 396 m in order to satisfy acceptance criteria for peak-to-peak vibrations. It should be noted that it takes for a lift about 66 meters to decelerate from 10 m/s to 0 m/s. This means that speed profile for a run from the entrance level to an upper floor that is shorter than 461.8 meters reduces to an ideal speed profile. For convenience, flight times for each speed policy from the entrance level to upper floors are reported in the last three columns in Table 3.

The traffic for both groups are simulated independently of each other using Building Traffic Simulator [11]. Several different traffic patterns are considered, see Table 2.

Table 2 Traffic patterns

Traffic pattern	Traffic components [percent]		
	Incoming	Outgoing	Interfloor
Up-peak	100	0	0
Down-peak	0	100	0
Two-way	50	50	0
Mixed	40	40	20

The simulations results are collected in Table 4. Handling capacity is measured in such a point where the average car load at starts is about 80 % of nominal load. From this one can see that setting the maximum speed to half decreases the handling capacity significantly while using optimized speed profile the handling capacity decreases slightly.

4.3 Long period implications on the service level of the elevator system

In the example the operation of the lift system can be classified in four distinctive modes based on the prevailing weather conditions; normal mode during calm weather, *enhanced sway operation* during moderately high wind, *high wind mode* and *storm mode*. During *storm mode*, the lift operation is ceased and the lift cars are positioned in safe parking areas. During *high wind mode*, the lifts are running at half speed independently of the source and destination floors.

Table 3 Building parameters and flight times from the entrance level, 0, to upper floors

Floor marking	Group A	Group B	Floor Height [m]	Level [m]	Flight time		
					P10	P5	PE
21	S	S	4	508	63.97	108.52	70.89
20	X	S	4	504	63.57	107.72	69.89
19	X	S	4	500	63.17	106.92	68.89
18	X	S	4	496	62.77	106.12	67.89
17	X	S	4	492	62.37	105.32	66.89
16	X	S	4	488	61.97	104.52	65.89
15	X	S	4	484	61.57	103.72	64.89
14	X	S	4	480	61.17	102.92	63.89
13	X	S	4	476	60.77	102.12	62.89
12	X	S	4	472	60.37	101.32	61.89
11	X	S	4	468	59.97	100.52	60.89
10	X	S	4	464	59.57	99.72	59.97
9	X	S	4	460	59.17	98.92	59.17
8	X	S	4	456	58.77	98.12	58.77
7	X	S	4	452	58.37	97.32	58.37
6	X	S	4	448	57.97	96.52	57.97
5	X	S	4	444	57.57	95.72	57.57
4	X	S	4	440	57.17	94.92	57.17
3	X	S	4	436	56.77	94.12	56.77
2	X	S	4	432	56.37	93.32	56.37
1	X	X	428	4	-	-	-
0	S	S	4	0			
S represents served floor while X represents express zone.							

Table 4 Handling capacities and waiting times

Performance measure	Speed policy	Traffic pattern, Group A			Traffic pattern, Group B		
		Up	Down	Two-way	Up	Down	Mixed
Handling capacity [number of passengers / 5min]	P10	107.1	53.9	164	65.2	88	90
	P5	70.7	35	110.6	50.4	62	75.2
	PE	102.9	49.7	143.5	64.4	84	88
Average waiting time [s]	P10	30.0	31.1	65.2	57.0	93.6	87.3
	P5	50.8	56.4	107	72.8	124	105
	PE	31.8	34.8	70.6	61.0	86.2	92.6

During enhanced sway operation, which is the focus of this paper, the variable speed profile is selected only when the car runs from a resonant floor to floors where the rope sway would induce unacceptably high in-car vibrations. This is an advancement over the traditional high wind mode, where, above a certain building sway threshold, all lift operations occur at half speed.

When it comes to designing tall buildings for occupant comfort under wind-induced motion a recent trend has been to evaluate the windstorms with a one-year recurrence interval. This recurrence interval is relevant to occupants' daily lives [12]. This is why a one year observation period was chosen for this study. The target for lift system design is that for normal buildings the *storm mode* is triggered less once per ten years and therefore during this observation period it is assumed the lift operation is never ceased due to sway.

The peak-to-peak acceleration limit of 20 gals set the lowest threshold to peak amplitude of 53 mm at the highest occupied floor. Between amplitudes of 53 and 88 mm the *enhanced sway operation* with variable speed profile may be used and the *storm mode* is activated at the amplitude of 170 mm, which corresponds approximately to a building acceleration of 13 gals. The exceeding of storm threshold is not considered for observation period.

Based on the acceleration characteristics of the case building (Fig. 13) it is expected that during the observation period the amplitude threshold of 53 mm is exceeded on 6 days and the amplitude of 88 mm on 1 day. The duration of these events cannot be gained from the return period data. To get an estimate for the calculation, the yearly wind speed data of the building location was acquired (Fig. 14) and days of high wind speeds where plotted in ½ hour segments (Fig. 15). From this four day sample data, it was estimated that high wind speed periods (> 50 m/s) can last up to 5 hours. For very high wind (> 60 m/s), there is just one measurement point, but taking into consideration the neighbouring high wind segments the duration of very high wind in set to 1 hour. It is noteworthy that the wind on 10.4.2018 is associated with a thunderstorm and due to its short duration it would most likely lack the power to excite the building.

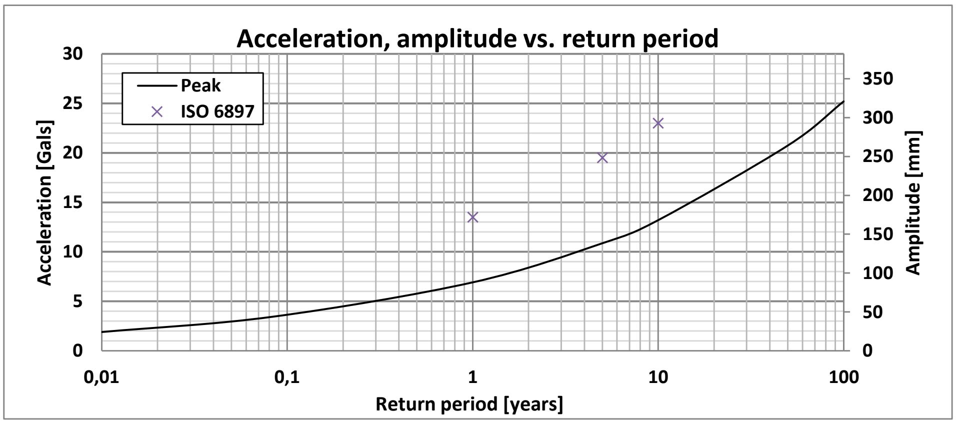

Figure 13 Acceleration and amplitude characteristics of the case study building

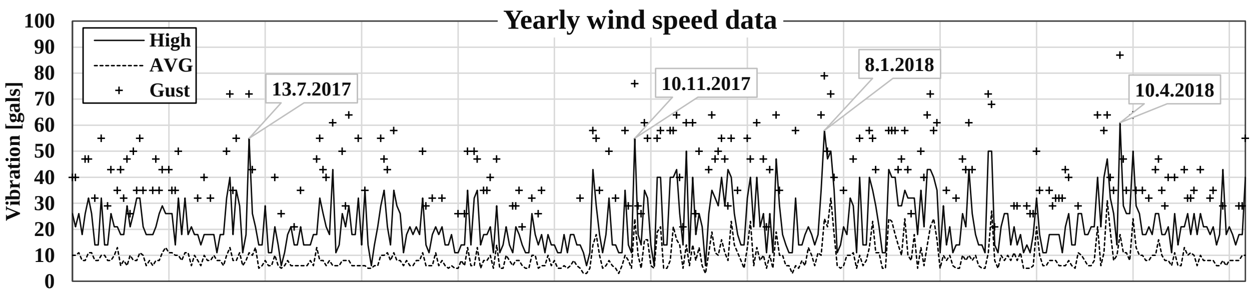

Figure 14 Yearly wind speed data for the location

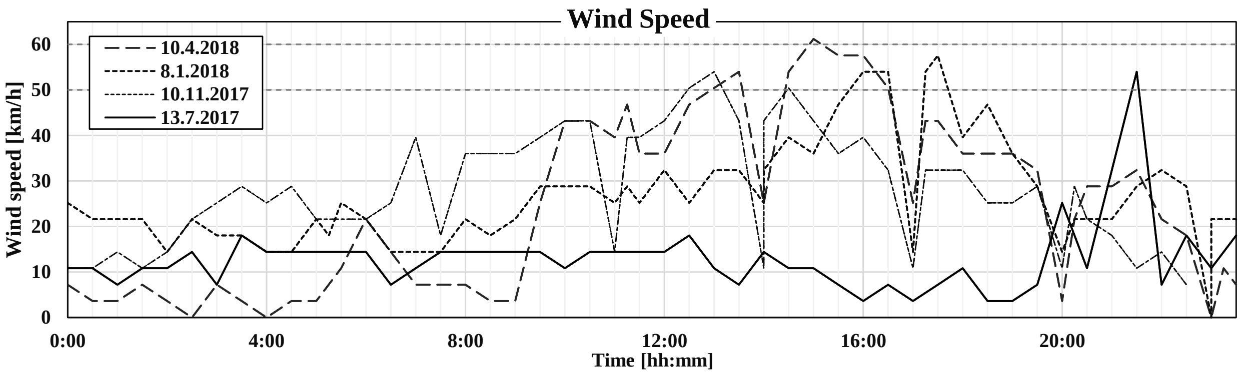

Figure 15 Wind speed data for high wind speed dates

The relative yearly handling capacity is calculated by formula:

$$HC_{relative} = 100\% \times \frac{t_{normal}}{t_{total}} + \frac{HC_{highwind}}{HC_{normal}} \times \frac{t_{highwind}}{t_{total}} + \frac{HC_{ench\_sway}}{HC_{normal}} \times \frac{t_{ench\_sway}}{t_{total}}, \quad (1)$$

where *HC* is handling capacity, *t* is time and t_{total} is total time (1 year). Index *normal* refers to when the lift is operating normally, *high wind* to *high wind mode* and *ench_sway* to *enhanced sway mode.* For simplicity, the two-way or mixed traffic is always assumed for the assessment.

5 RESULTS AND DISCUSSION

In this paper, a multi-physics approach has been used for computing in-car vibrations for different component selections, driving parameters and sway conditions of the building.

By optimization of the speed profile during building sway, a solution can be found for the majority of sway conditions, which fulfils the ride comfort requirement and which increases the lift flight time only moderately. This *enhanced sway operation* allows keeping the handling capacity of the lift system high even on windy days.

For a shuttle lift (Group A) with the *enhanced sway operation*, during the observation period of one year, on 6 days the handling capacity is reduced to 88 % for a period of 5 hours, for 1 day per year the handling capacity is reduced to 67 % for 1 hour and the rest of the time the handling capacity is nominal. The yearly relative handling capacity is 99.953 %. Without the *enhanced sway operation,* on 6 days the handling capacity is reduced to 67 % for a period of 5 hours and on one day per year for one hour. For the rest of the time the handling capacity is nominal. The yearly relative handling capacity is 99.885 %. For Group B, the handling capacity is reduced to 98 % for *enhanced sway operation* and to 84 % for *high wind mode*. The yearly relative handling capacity is 99.991 % with *enhanced sway operation* and 99.942 % without it.

Overall, through this very simplified example, it can be seen that there is no major effect to the handling capacity on yearly level with either approach on either group. However, especially for the shuttle lifts (Group A) without *enhanced sway operation*, it can be expected that during the reduced speed operation a peak in lift traffic will occur which will cause longer waiting periods and longer flight times (see Table 3 and Table 4). This will not go unnoticed by the lift users. By using *enhanced sway operation,* the period on half speed service is considerably reduced and is less likely to occur during peak traffic. Also, the increase in waiting time and flight times during *enhanced sway operation* is less likely to create passenger discomfort.

These results can be assumed to be fairly representative of modern buildings designed with high occupant comfort in mind (offices, hotels, residential buildings). For other structures (TV and observation towers) the outcome might be considerably different.

The Transient Dynamic Computation enables the evaluation of the performance of mega-high rise lifts from a much wider perspective than has been previously possible. This paper presents a multidisciplinary approach by using a practical example where the dynamic computation is combined with ride comfort requirements, traffic-analysis, sway characteristics of the building and climate information. The example demonstrates that through this process it is possible to minimize the negative impacts of building sway to the performance of the lift system. For a practical implementation of this approach there seems to be two possibilities; either to assess the performance in sway conditions separately for individual runs and apply traffic modes precisely based on actual traffic forecast for high accuracy or establish a generic database of predefined cases for quick fit-for-purpose speed policy selection.

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Using the Monte Carlo Simulation to Evaluate the Round-Trip Time Under Destination Group Control

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Abstract. Lift traffic calculations for planning purposes typically use formulae, or simulation software which applies a traffic control system to dispatch lifts. Formulae methods rely on simplifying the modelling exercise so that the operation of the lifts can be described in mathematical equations. These equations are transparent and repeatable. Simulation is more sophisticated but relies on many advanced dispatching and other complex decisions which are hidden from the user. This can be controversial when results from different simulation software are compared. Monte Carlo Simulation is a calculation tool that does not require simplifying the modelling exercise and can thus produce results that are more representative of reality but are repeatable. In this paper the authors demonstrate how Monte Carlo Simulation can be used to evaluate destination control (also known as hall call allocation) for any traffic mix (incoming, outgoing, inter-floor). The technique requires fewer simplifications than formulae-based methods. It does not require a dispatcher (but requires a simple allocation methodology), making it a supplier independent way to evaluate the application of this form of traffic control.

1 INTRODUCTION

The Monte Carlo simulation method is a powerful numerical tool that can be used to solve complex problems. It has been applied in lift traffic systems [1, 2] and specifically to find the round-trip time [3] and the travelling time [4].

The aim of this paper is to present a method using Monte Carlo simulation to find the value of the round-trip time under destination group control. The round-trip time in this context under the mixed traffic condition is defined as follows:

The average time between the lowest elevator reversal to the following lowest elevator reversal.

A previous paper has presented a method to evaluate the round-trip time under conventional group control [5]. Under conventional group control, passengers arriving for lift service simply board the first available lift that arrives at the landing. Under destination group control [6, 7, 8, 9, 10, 11], passengers arriving for lift service are allocated a specific lift in the group (based on their declared destination floor) and must only board the allocated lift when it arrives at the landing.

There are several distinct steps that are followed in evaluating the round-trip time:

1. Passenger origins and destinations are randomly generated based on the origin-destination matrix.
2. The passengers are split into up passengers and down passengers.
3. The passengers are then sorted based on either their origins or based on their destinations.
4. The passengers are then grouped and allocated to the corresponding lift cars.
5. The round trips for each of the cars required to deliver the passengers are calculated, including the kinematic time [12].
6. The average of the round trips for the L lift cars is taken.
7. The procedure is repeated for many trials/scenarios.
8. The average of all the round-trip times is taken as the representative value of the round-trip time under destination group control.

The methodology for generating passenger origin destination pairs is presented in section 2. Section 3 outlines the methodology used for grouping passengers in cars under destination group control (either by origins or by destinations). Section 4 presents results for a sample building and discusses these results. Conclusions are drawn in section 5.

2 GENERATION OF PASSENGERS

At the heart of the Monte Carlo simulation methods is the random generation of passenger origin-destination pairs. A systematic method for generating passenger origin destination pairs is the use of the origin-destination (OD) matrix [13, 14, 15] where it assumes that any floor in the building is either an occupant floor or an entrance floor. A more generalised type of OD matrix allows all floors in the building to be simultaneously an occupant and entrance floor [16].

The origin destination matrix is first compiled using the entrance biases for the entrance floors and the percentage populations for the occupant floors, in addition to the mix of traffic of incoming, outgoing, inter-floor and inter-entrance. This produces a square matrix, the dimensions of which are equal to the total number of floors in the building. The matrix has a zero diagonal and all its elements add up to a total of 1. Thus, it represents the probability density function (pdf). It is then integrated and converted to a cumulative distribution function (cdf). Random sampling is then carried out in order to pick origin destination pairs for passengers.

3 PASSENGER GROUPING METHODOLOGY

By its very nature, using the Monte Carlo simulation method for finding the round-trip time under any set of conditions requires that the allocation methodology for the passengers to the lift cars be simple and intuitive. The place for complicated landing call allocation methodologies belong to simulation packages and real-life dispatchers, rather than to the Monte Carlo simulation [17]. This is in recognition of the fact that the Monte Carlo simulation method is effectively a "calculation" tool as opposed to a simulation tool. More information about group control can be found in [18] and [19].

In this section the method of allocating passengers to the lift cars in the group is discussed. Allocating the passengers to cars in the group can be referred to using the generic term of: "passenger grouping". An interesting introduction to this concept is contained in [20].

The following assumptions have been made:

1. Each lift car will serve P passengers in each round trip. This does not necessarily imply that it will have P passengers simultaneously present inside the car at any point during the journey (although this does happen in the cases of 100% incoming traffic or 100% outgoing traffic). It simply means that during one full round trip, P passengers board and alight from that lift car.
2. The controller has full advance knowledge of the passenger origins and destinations and hence can allocate passengers to the lifts cars as necessary.
3. The Origin-Destination (OD) matrix is compiled using the entrance biases, the occupant floor populations and the mix of traffic.
4. In each trial, $L \cdot P$ passengers are generated randomly, where L is the number of lifts in the group. Each passenger has an origin-destination pair of floors (generated in accordance with the OD matrix).
5. The passengers are then sorted as up passengers first (in ascending order) and then down passengers (in descending order).
6. In the destination control RTT calculation (grouping by origin mode), the passengers are sorted based on their origins, and allocated to each lift car, P passengers at a time.
7. In the destination control RTT calculation (grouping by destination mode), the passengers are sorted based on their destinations, and allocated to each lift car, P passengers at a time.

A practical example is graphically shown in this section. It is assumed that a building has a total of 20 floors (including any entrance floors). There are three lift cars in the group (i.e., L=3) and the number of passengers served by each car in one round trip is 5 (i.e., P=5). Thus, in one epoch there are 15 passengers to be generated, allocated to the three cars and delivered to their destinations.

In every trial (scenario) a new set of 15 passengers are generated. An example of one trial/scenario for this building is shown in Figure 1. The up-travelling passengers have been placed on the left hand-side of the figure; and the down travelling passengers have been placed on the right-hand-side of the figure. It must be emphasised that due to the randomness of the passenger origin-destinations, it is possible that, in some trials/scenarios, all 15 passengers are up travelling passengers, or in other trials/scenarios, all 15 passengers are down travelling passengers. In this trial/scenario shown in Figure 1, 7 up passengers have been generated and 8 down passengers have been generated.

The passengers are then grouped by origins as shown in Figure 2. Alternatively, they can also be grouped by their destinations as shown in Figure 3.

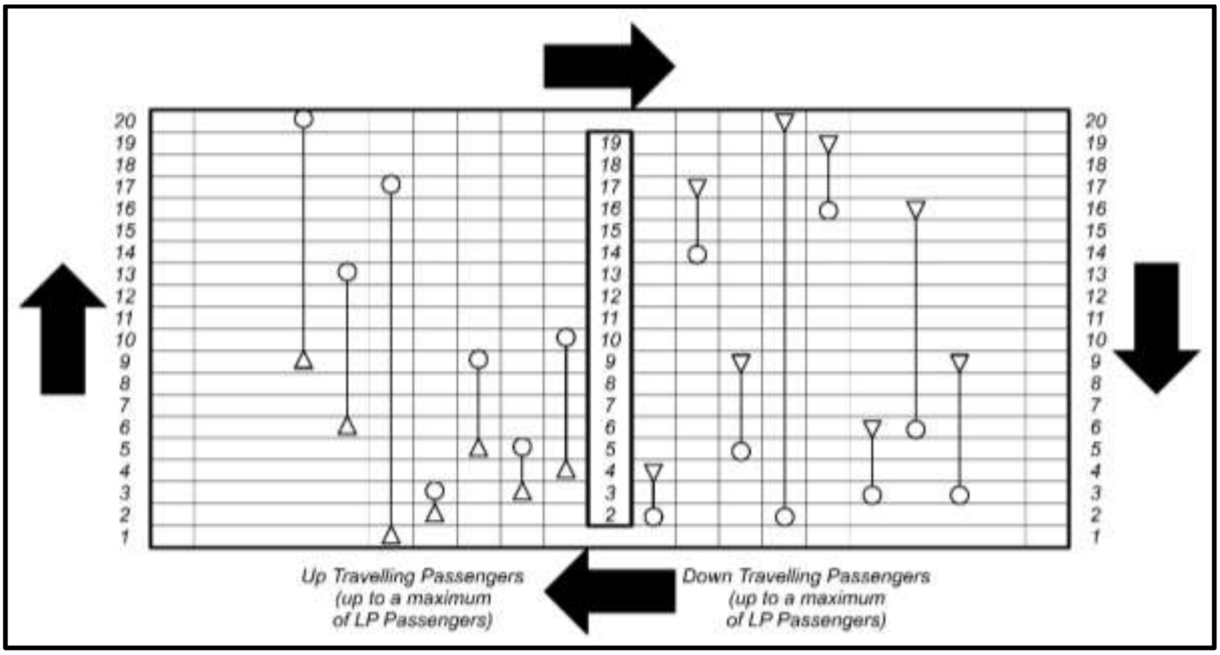

Figure 1 Generating 15 passengers (5 x 3) in a building with 20 floors

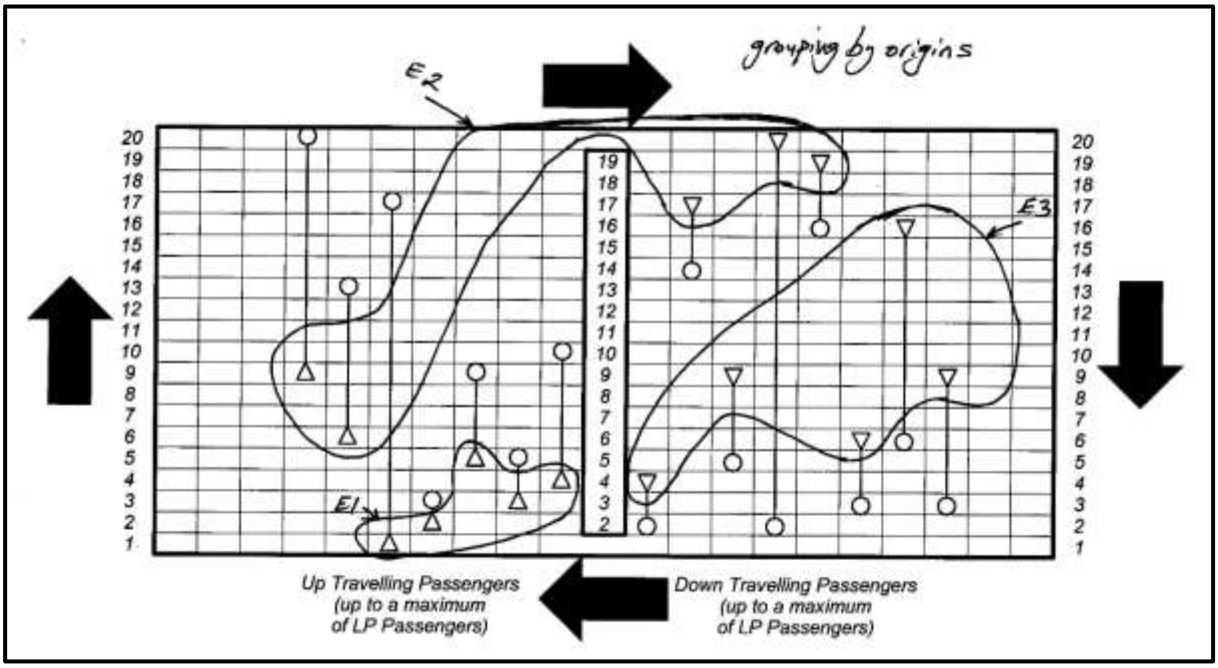

Figure 2 Grouping the passengers in lift cars based on the origin floors of their journeys

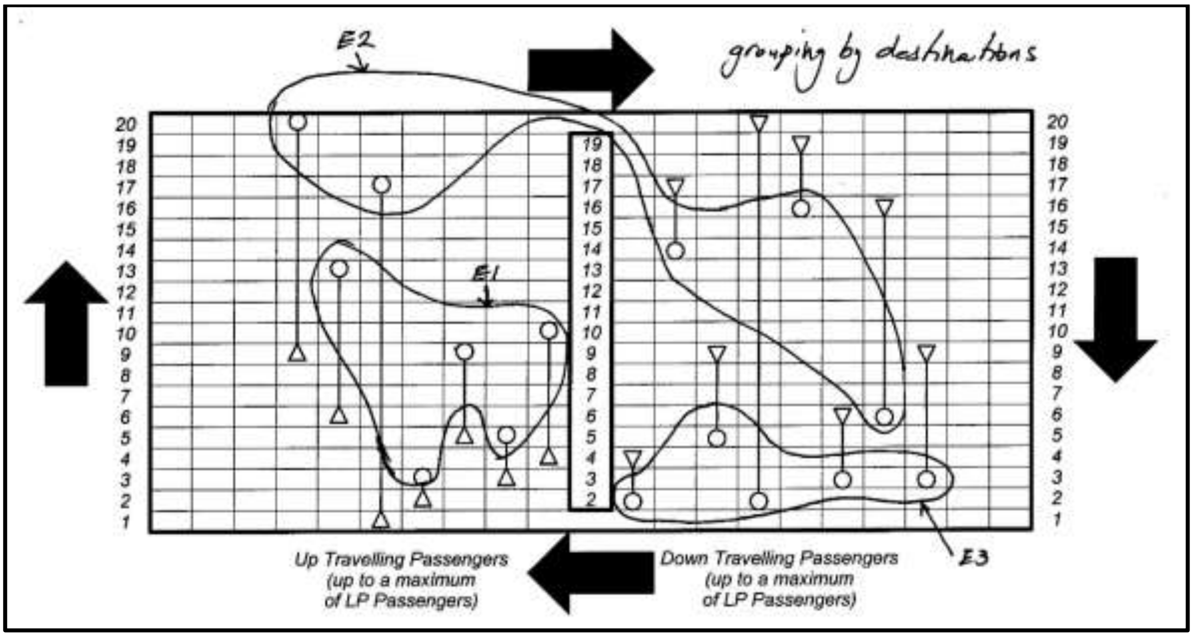

Figure 3 Grouping the passengers in lift cars based on the destination floors of their journeys

It is worth noting that in this example, the point at which the grouping commenced was the lowest origin up travelling passenger (or the lowest destination up travelling passenger. This choice is the simplest one to select. It would have been possible to start at other points. The four most obvious choices are listed below:

1. The lowest origin (or destination) up travelling passenger (as used in the example in this section).
2. The topmost origin (or destination) down travelling passenger.
3. Randomly picking an origin (or destination) for any passenger in each trial.
4. Picking the first generated passenger in an epoch and using his/her origin (or destination) as the starting point. This method is likely to yield the same result as option 3 above.

It is likely that the most representative value of the round trip time will result from using option 3 or 4, 50% of the scenarios picking an origin and 50% of the scenarios picking a destination.

4 RESULTS AND DISCUSSION

In order to quantitatively assess some of the results from the software, a sample building was used. The parameters of the building and lift system are shown below.

Sample building parameters

Number of entrance floors: M = 2

Number of occupant floors: N = 12

Entrance bias: 0.3 for the basement; 0.7 for the ground floor.

Number of lifts in the group: L=4

Door opening time: t_{do} = 2 s

Door closing time: t_{dc} = 3 s

Passenger transfer time: t_{pi}, t_{po}= 1.2 s

Number of passengers served by a lift car in one round trip: P= 12 passengers

Rated speed: v= 2.5 m/s.

Rated acceleration: a= 1 m/s^2.

Rated jerk: jerk = 1 m/s^3.

Population: 1200 persons equally distributed over 12 occupant floors.

Floor heights in m: df= [5 5 4.5 4.5 4.5 4 4 4 3.5 3.5 3.5 3 3 3]

Number of trials: n= 10 000

Table 1 contains the values of the round-trip time to one decimal place, using 10000 trials (n=10 000). The round-trip time was evaluated for different traffic conditions, such as the morning peak with traffic mix (incoming: outgoing: interfloor) of 85%:10%:5% and the lunchtime traffic mix of 45%:45%:10% [21].

Table 1 Results for the sample building

	Pure incoming traffic traffic mix 100%:0%:0%	Morning Traffic traffic mix 85%:10%:5%	Balanced traffic mix 50%:50%:0%	Lunchtime traffic mix 45%:45%:10%	Pure outgoing traffic traffic mix 0%:0%:100%
Conventional control (i.e., passenger boards the first available lift)	152.3 s	166.6	174.2 s	179.9 s	152.3 s
Destination group control (with passenger grouping into the lift cars by passenger destinations)	105.6 s	121.5	139.3 s	144.4 s	143.5 s
Destination group control (with passenger grouping into the lift cars by passenger origins)	143.5 s	153.4	139.3	144.4 s	105.6 s

Some comments on these results are presented below:

1. Invariably, the value of the round-trip time under destination control is smaller than the value under conventional control. This represents a potential hypothetical boost in the handling capacity (assuming that the lift cars continue to serve P passengers in each round trip). For example, a reduction in the value of the round-trip time from 152.3 s down to 105.6 s due to the introduction of destination control represents a potential boost in handling capacity of 44.2%.
2. The reduction in the value of the round-trip time is greater in the case of incoming traffic when the passengers are grouped into lift car by destination (rather than their origins).
3. Similarly, the reduction in the value of the round trip is greater in the case of outgoing traffic when the passengers are grouped into lift cars by origins (rather than destinations).
4. Although not shown in these results, the reduction in the value of the round trip will increase as the number of lifts in the group are increased. This is confirmed by other research [22].
5. There is no difference between grouping passengers by origin or by destination under balanced traffic conditions.
6. It is useful to examine the boost under handling capacity under destination group control compared to conventional control.
   a. The value of the RTT under conventional control, pure incoming traffic (100% incoming, grouped by destination): 152.3 s.
   b. The value of the RTT under destination group control, pure incoming traffic (100% incoming) grouped by destination: 105. 6 s.
   c. Thus, the boost in handling capacity is equal to 152.3/105.6 = 144.2% or a boost of 44.2%.

7. However, the boost in handling capacity for lunchtime traffic is much smaller, as shown by the calculations shown below.
    a. The value of the RTT under destination group control during lunchtime traffic (45:45:10) is equal to 144.4s.
    b. The value of the RTT under conventional group control during lunchtime is 179.9 s.
    c. Thus, the boost is only a boost of 179.9/144.4 = 124.6% or a boost of only 24.6%, compared to a boost of 44.2% under incoming traffic conditions.

    This result corroborates other research [6] that warns against reducing the number of lifts in the design based on the expected boost in handling capacity under incoming traffic conditions, without considering that the boost in handling capacity under lunchtime conditions is much smaller.

5 CONCLUSIONS

The Monte Carlo simulation method is a powerful numerical tool that can be used to calculate the value of the lift round trip time under destination group control. An epoch has been used as the basis for each trial or scenario of the Monte Carlo Simulation. An epoch is a term borrowed from neural networks and comprises the random generation of LP passengers' origin-destination pairs, and allocating them to the L lift cars, P passengers per car.

The trial or scenario is repeated a large number of times (e.g., 100 000 or 1 000 000) and the average value of the round-trip time is evaluated and taken as representative of the true value of the round-trip time under destination group control.

As expected, the value of the round-trip time under destination group control was consistently smaller than the value under conventional group control. The ratio of the two round trip times was presented as a representative of the boost in handling capacity that results from the application of destination group control. As expected, the boost in handling capacity was largest in the case of incoming traffic conditions (when passengers were grouped by destinations) and hovered around 1.45 (i.e., 45% boost in handling capacity). The boost was smaller under lunchtime traffic conditions.

The group of passengers into the lift cars was carried out based on contiguous passenger origins first and then destinations. Grouping based on destinations was advantageous under incoming conditions, while grouping based on origins was advantageous under out-going traffic conditions.

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