# The Maximum Number of Passengers Boarding a Lift in Office Buildings Based on Automated Passenger Counts

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**Abstract.** While a lift is serving a landing but is already carrying several passengers, the passengers on the landing need to decide whether to board the lift or wait for the next. The boarding decision is made by contrasting the space available in the car to the required space, which assumedly depends on physical, behavioural and social factors. As already observed in the 1960s, passengers do not typically fill a lift up to its rated passenger capacity, i.e., the maximum number of passengers in a lift car that must not be exceeded due to lift safety standards. If, in lift traffic design, the maximum number of passengers in a lift car is assumed to equal rated passenger capacity, the lift group may not reach its required handling capacity in practice. Regardless the known contradiction, the maximum number of passengers accepting to board a lift has not been studied systematically. This paper aims at filling the gap by analysing automated passenger counts in three existing office buildings. Car capacity factor is defined as the ratio of maximum passenger count in a lift to rated passenger capacity. The highest car capacity factors are derived for different traffic conditions as well as related to both handling capacity and pedestrian level of service criteria. The results indicate diverse behaviours when passengers are about to board a lift.

## 1 INTRODUCTION

As a part of their journey in a multi-storey building, lift passengers routinely decide whether they board a lift that already carries several passengers or wait for the next lift. To board a lift, passengers require free space to satisfy not only their physical needs but also personal preferences. Factors that affect the behaviour may include, but are not limited to, culture, gender, building type, social group, time of day and experienced waiting times. Lift safety standards restrict *maximum available car area* for a lift with a particular *rated load* [1,2]. It has been observed already in the 1960s that passengers do not typically fill lifts up to their capacities although behaviour varies depending on rated load and time of day [3].

Regardless the early observations, it is surprising that the maximum number of passengers accepting to board a lift has not been studied systematically. The assumed maximum number of passengers accommodated by a lift, i.e., *passenger capacity*, is one of the key parameters in lift traffic design, which aims at defining a suitable lift installation for a building, e.g., the number of lifts as well as their rated loads and speeds [e.g. 4]. If passenger capacity assumed in the design is higher than passengers actually accept, the lifts may not be able to transport as many passengers as indicated. In contrast, if more passengers than assumed by passenger capacity accept to board in practice, the lift installation may be somewhat oversized with respect to the demand.

Passenger capacity can be defined either as *rated* or *area-based passenger capacity*. Rated passenger capacity is typically obtained by dividing rated load by average passenger mass, e.g., 75 kg in Europe. Maximum available car area per passenger in a lift loaded up to its rated passenger capacity decreases as rated load increases [1,2]. For example, area per passenger equals 0.20 $m^2$ for an 800 kg lift and 0.16 $m^2$ for a 2000 kg lift. On the other hand, area-based passenger capacity can be derived by dividing maximum available car area by the area required by an average passenger, where the area of a design ellipse, 0.21 $m^2$, is typically assumed. The design ellipse was derived using the 95th percentile body depth and shoulder width of male laborers in the USA to allow for personal articles, psychological preferences and body sway [5]. If a passenger is modelled by the design ellipse, standard-sized lift cars can accommodate passengers from 57% to 70% of their rated passenger capacities for a 2000 kg lift and an 800 kg lift, respectively [6]. Thus, depending on the method, passenger capacity of a 2000 kg lift can be either 26, 20 or 15 passengers.

This paper studies the maximum number of passengers accepting to board a lift in three office buildings operating under normal circumstances. Required data was collected by *Lift Performance Analyser* (LPA), which is a stand-alone sensor device temporarily installed in a lift [7]. The LPA detects floor levels when the lift stops and acceleration rates using an accelerometer, which allows to calculate lift group *handling capacity* with measured lift performance times. In addition, it uses 3D camera technology with human detection algorithms to identify boarding and alighting passengers with greater than 95% accuracy. The passenger counts are used to derive car capacity factors and handling capacity ratios, which define how full a lift is and how close to handling capacity measured passenger demand is, respectively.

## 2 DEFINITIONS

The stop-wise counts of passenger transfers recorded by the LPA yield the number of passengers carried by a lift at any time. More formally, let *S* denote the set of lift stops, which is indexed by *i*. It is assumed that the stops are ordered by the time of occurrence so that $i-1$ refers to the stop preceding stop $i$. Furthermore, the number of alighting and boarding passengers during a stop are denoted by $a_i$ and $b_i$. The number of passengers, $p_i$, inside the lift after stop *i* evolves cumulatively,

$$p_i = p_{i-1} - a_i + b_i. \tag{1}$$

Stops are associated with period *T* of fixed length. Period length of five minutes is assumed unless stated otherwise. For example, *T* may refer to a five-minute period 10:55-11:00 excluding the end time. The period, to which a stop belongs, is determined by the time of arrival at the stop-floor. Car capacity factor *CCF* is defined as the ratio of maximum number of passengers to rated passenger capacity *PC* among the set of stops $S_T$ during period *T*,

$$CCF_T = 100\% \times \max_{i \in S_T} p_i / PC. \tag{2}$$

The number of passengers in a lift can also be related to maximum available car area *CA*, which is described by available area per passenger *APP*:

$$APP_T = CA \Big/ \max_{i \in S_T} p_i. \tag{3}$$

The maximum available car area is defined by safety standards. Area per passenger allows to classify lifts according to pedestrian level of service criteria for waiting and queuing areas [5]. For example, human touch zone, i.e., LOS E, corresponds to an occupancy of 0.19-0.28 $m^2$ per person.

Passenger demand $PD_T$ equals the sum of all boarding passengers,

$$PD_T = \sum_{i \in S_T} b_i. \tag{4}$$

Handling capacity *HC5* defines the maximum sustainable number of passengers per five minutes that a lift group can transport for uppeak traffic with under an average loading of 80% of rated passenger capacity. Handling capacity ratio *HCR* for a five-minute period *T* is the ratio of passenger demand and handling capacity [8,9],

$$HCR_T = 100\% \times PD_T/HC5. \tag{5}$$

Handling capacity ratio may exceed 100% since a full collective lift group has higher handling capacity in mixed and downpeak traffic than in uppeak traffic [e.g. 10]. Handling capacity ratio can also be calculated for periods longer than five minutes by properly scaling passenger demand.

## 3 STUDIED BUILDINGS AND LIFTS

Site surveys were conducted during 2018 and 2019 in three European office buildings with typical lift car sizes (see Table 1 for details).

**Table 1 Office A, B and C building data**

| | **Office A** | **Office B** | **Office C** |
|---|---|---|---|
| **Region** | South Europe | South Europe | Central Europe |
| **Predominant religion** | Islam | Islam | Christian |
| **Tenancy** | Single | Multiple | One big tenant |
| **Absence rate [%]** | 20 | Unknown | 20 |
| **Number of floors** | 29 | 29 | 15 |
| **Measurement time** | 6:35…19.59 | 6:48…18:59 | 6:45…20:00 |
| **Morning peak** | 8:30…9:30 | 8:30…9:30 | 8:30…9:30 |
| **Lunch peak** | 12:00…13:45 | 11:55...13:40 | 11:55…14:35 |
| **Evening peak** | 17:55…18:25 | 17:50…18:20 | 16:55…17:25 |
| **Number of lifts in group** | 6 | 6 | 5 |
| **Group control** | Full collective | Full collective | Full collective |
| **Rated speed [m/s]** | 2.5 | 2.5 | 2.5 |
| **Rated load [kg]** | A1…A4, A6: 1000<br>A5: 1200 | B2…B6: 800<br>B1: 1000 | C2, C3: 1200<br>C1, C4, C5: 1500 |
| **Rated passenger capacity [persons]** | A1…A4, A6: 13<br>A5: 16 | B2…B6: 10<br>B1: 13 | C2, C3: 16<br>C1, C4, C5: 20 |
| **Area per passenger at capacity [m$^2$]** | A1…A4, A6: 0.185<br>A5: 0.175 | B2…B6: 0.200<br>B1: 0.185 | C2, C3: 0.175<br>C1, C4, C5: 0.170 |
| **Lift shape** | Long and narrow | Long and narrow | Varying widths and depths |
| **Handling Capacity [persons/5-min]** | 95 (79 without A6) | 91 | 109 |
| **Personal accessories** | No moving aids, summer clothing | No moving aids, summer clothing | Normal |
| **Passenger waiting times** | Unsatisfactory | Excellent | Satisfactory |

The chosen buildings were also high enough so that lifts played the key role in vertical transportation. In other respects, the buildings were chosen relatively randomly. Office A building management had reported traffic problems and asked for a survey. Office B was known to have good passenger service quality and was chosen for comparison purposes since it is very similar to Office A. In both cases, building management allowed LPAs to be installed in lifts for collecting data, but observations were limited to the main entrance floor due to their security policy. Office C is located in another part of Europe than offices A and B. The lifts of Office C were on the limit of being able to satisfy the passenger demand.

Data collection started before 7 a.m. and ended by 8 p.m. at the latest. Periods that were included in morning uppeak, mid-day lunch-peak and evening downpeak, were decided when analysing data and seeing when the peaks take place in each building. In Office B, data was collected for one day only, while Office A and C were studied for a couple of days. According to the observations, all lifts in the buildings were in normal use, but the sensor in lift A6 failed during the second day.

Table 2 presents average and maximum handling capacity ratios across the 5-minute periods of the defined peak times, where day 2 results for Office A are based on only five lifts. During morning uppeak in Office A, maximum handling capacity ratio exceeded 100%, which also implies that peak passenger demand exceeded handling capacity. Accordingly, peak demand in the morning in Office B is clearly below handling capacity even during the worst 5-minute period. In Office C, morning peak demand is about the same as handling capacity during the first two measurement days but exceeds it during the last measurement day.

According to the definition of handling capacity ratio, also passenger demands at other times of the day are compared to uppeak handling capacity. With full collective control, a lift group can handle higher passenger demands in lunch-peak and downpeak than in uppeak. Therefore, handling capacity ratios greater than 100% do not necessarily indicate insufficient handling capacity.

**Table 2 Average and maximum handling capacity ratios during peak times**

| **Building** | **Day** | **Average *HCR* [%]** | | | **Maximum *HCR* [%]** | | |
|---|---|---|---|---|---|---|---|
| | | **Morning** | **Lunch** | **Evening** | **Morning** | **Lunch** | **Evening** |
| A | 1 | 81 | 102 | 91 | 108 | 130 | 137 |
| | 2 | 73 | 85 | 67 | 102 | 121 | 135 |
| B | 1 | 48 | 59 | 56 | 70 | 109 | 90 |
| C | 1 | 67 | 73 | 75 | 96 | 117 | 111 |
| | 2 | 69 | 81 | 75 | 94 | 120 | 102 |
| | 3 | 65 | 79 | 76 | 107 | 104 | 103 |

In Office A and B, evening peak passenger demands were about 30% higher than in the morning implying rather fixed times to leave the office. The sharpness of evening peak was a bit surprising. In Office C, evening peak passenger demands were on average 6% greater than in the morning. Office A seems similar to Office C based on the ratio of lunch-peak handling capacity ratio to the one of uppeak. This may arise from the tenancy: Office A was a single-tenant office, and Office C had one big tenant occupying most floors. On the other hand, Office B was a multi-tenant office. In these single-tenant offices, the highest passenger demands during lunch-peak were about 20% greater than during uppeak, but in the multi-tenant office the difference was even more than 50%. However, strong conclusions cannot be made based on this amount of data.

## 4 MAXIMUM CAR CAPACITY FACTORS

Table 3, 4 and 5 present the highest measured car capacity factors and the respective minimum areas per passenger in Office A, B and C, respectively. The densities are further classified by pedestrian level of service criteria. The maximum car capacity factors are also averaged across the lifts. However, average areas per passenger cannot be given due to different car sizes.

According to the measurements, passengers seem to accept the highest car capacity factors during lunch-peak. Car capacity factors are also higher during downpeak than during uppeak. This does not necessarily mean that people would be more eager going for lunch or to home than coming to work. The trend might arise from passengers' previous experiences on waiting for a lift. At the main lobby, passengers know that the next lift will arrive soon. On normal office floors, passengers may expect that the next lift will arrive only after a long wait. Alternatively, during lunch-peak, passengers often travel in socially connected groups, which may motivate the group to board even a crowded lift as a whole [11].

**Table 3 Maximum car capacity factors and minimum areas per passenger in Office A**

| **Day** | **Lift** | **Maximum *CCF* [%]** | | | **Minimum *APP* [m$^2$] and *LOS*** | | |
|---|---|---|---|---|---|---|---|
| | | **Morning** | **Lunch** | **Evening** | **Morning** | **Lunch** | **Evening** |
| 1 | A1 | 69 | 92 | 100 | 0.267 (E) | 0.200 (E) | 0.185 (F) |
| | A2 | 85 | 100 | 85 | 0.218 (E) | 0.185 (F) | 0.218 (E) |
| | A3 | 77 | 100 | 85 | 0.240 (E) | 0.185 (F) | 0.218 (E) |
| | A4 | 85 | 85 | 92 | 0.218 (E) | 0.218 (E) | 0.218 (E) |
| | A5 | 69 | 81 | 88 | 0.255 (E) | 0.215 (E) | 0.200 (E) |
| | A6 | 92 | 92 | 92 | 0.200 (E) | 0.200 (E) | 0.200 (E) |
| | *Average* | *79* | *92* | *90* | | | |
| 2 | A1 | 85 | 100 | 100 | 0.218 (E) | 0.185 (F) | 0.185 (F) |
| | A2 | 92 | 108 | 85 | 0.200 (E) | 0.171 (F) | 0.218 (E) |
| | A3 | 85 | 108 | 100 | 0.218 (E) | 0.171 (F) | 0.185 (F) |
| | A4 | 92 | 100 | 108 | 0.200 (E) | 0.185 (F) | 0.171 (F) |
| | A5 | 69 | 88 | 94 | 0.255 (E) | 0.200 (E) | 0.187 (F) |
| | *Average* | *85* | *101* | *97* | | | |

As Office A did not have sufficient handling capacity, car capacity factor exceeded 80% many times and even reached 100% occasionally. At minimum, area per passenger dropped below 0.19 m$^2$. Accordingly, level of service degraded to class F. The results indicate differing behavioural patterns between the measurement days. Both average and maximum handling capacity ratios were greater during day 1 than during day 2. On the contrary, passengers accepted higher car capacity factors during day 2, which could have occurred due to long waiting times experienced during day 1. This observation could also result from random variation.

**Table 4 Maximum car capacity factors and minimum areas per passenger in Office B**

| Lift | Maximum *CCF* [%] | | | Minimum *APP* [m$^2$] and *LOS* | | |
|---|---|---|---|---|---|---|
| | Morning | Lunch | Evening | Morning | Lunch | Evening |
| B1 | 69 | 69 | 62 | 0.267 (E) | 0.267 (E) | 0.300 (D) |
| B2 | 60 | 90 | 70 | 0.333 (D) | 0.222 (E) | 0.286 (D) |
| B3 | 70 | 80 | 80 | 0.286 (D) | 0.250 (E) | 0.250 (E) |
| B4 | 60 | 70 | 70 | 0.333 (D) | 0.286 (D) | 0.286 (D) |
| B5 | 70 | 80 | 100 | 0.286 (D) | 0.250 (E) | 0.200 (E) |
| B6 | 80 | 80 | 70 | 0.250 (E) | 0.250 (E) | 0.286 (D) |
| *Average* | *68* | *78* | *75* | | | |

**Table 5 Maximum car capacity factors and minimum areas per passenger in Office C**

| Day | Lift | Maximum *CCF* [%] | | | Minimum *APP* [m$^2$] and *LOS* | | |
|---|---|---|---|---|---|---|---|
| | | Morning | Lunch | Evening | Morning | Lunch | Evening |
| 1 | C1 | 75 | 70 | 75 | 0.227 (E) | 0.243 (E) | 0.227 (E) |
| | C2 | 88 | 94 | 75 | 0.200 (E) | 0.187 (F) | 0.233 (E) |
| | C3 | 69 | 106 | 81 | 0.255 (E) | 0.165 (F) | 0.215 (E) |
| | C4 | 60 | 65 | 65 | 0.283 (D) | 0.262 (E) | 0.262 (E) |
| | C5 | 70 | 70 | 70 | 0.243 (E) | 0.243 (E) | 0.243 (E) |
| | *Average* | *72* | *81* | *73* | | | |
| 2 | C1 | 65 | 70 | 65 | 0.262 (E) | 0.243 (E) | 0.262 (E) |
| | C2 | 81 | 75 | 69 | 0.215 (E) | 0.233 (E) | 0.255 (E) |
| | C3 | 75 | 88 | - | 0.233 (E) | 0.200 (E) | - |
| | C4 | 85 | 70 | 80 | 0.200 (E) | 0.243 (E) | 0.213 (E) |
| | C5 | 60 | 60 | 70 | 0.283 (D) | 0.283 (D) | 0.243 (E) |
| | *Average* | *73* | *73* | *71* | | | |
| 3 | C1 | 60 | 65 | 80 | 0.283 (D) | 0.262 (E) | 0.213 (E) |
| | C2 | 81 | 81 | 88 | 0.215 (E) | 0.215 (E) | 0.200 (E) |
| | C3 | 88 | 81 | 94 | 0.200 (E) | 0.215 (E) | 0.187 (F) |
| | C4 | 65 | 80 | 80 | 0.262 (E) | 0.213 (E) | 0.213 (E) |
| | C5 | 60 | 65 | 80 | 0.283 (D) | 0.262 (E) | 0.213 (E) |
| | *Average* | *71* | *75* | *84* | | | |

In Office B, peak passenger demands did not exceed handling capacity. As a result, car capacity factors rarely exceeded 80% and level of service never degraded to F. On the other hand, the lifts were the smallest among the studied buildings, which implies the largest area per passenger with a car capacity factor of 100%.

Fig. 1, 2 and 3 present maximum car capacity factors measured for each lift in Office A, B and C at different times of the first measurement day. The other days were quite similar to the first day but with some exceptions. In Office A, car capacity factor temporarily exceeded 80% several times and in several lifts during the first measurement day. The second day provided similar data with the exception that car capacity factor also exceeded 100%. In Office B, 80% car capacity factor was rarely exceeded. In Office C, over 80% car capacity factor was measured a couple of times per day. Also over 100% car capacity factors were observed during the first day for several sequential starts of lift C3, which did not happen during the other measurement days.

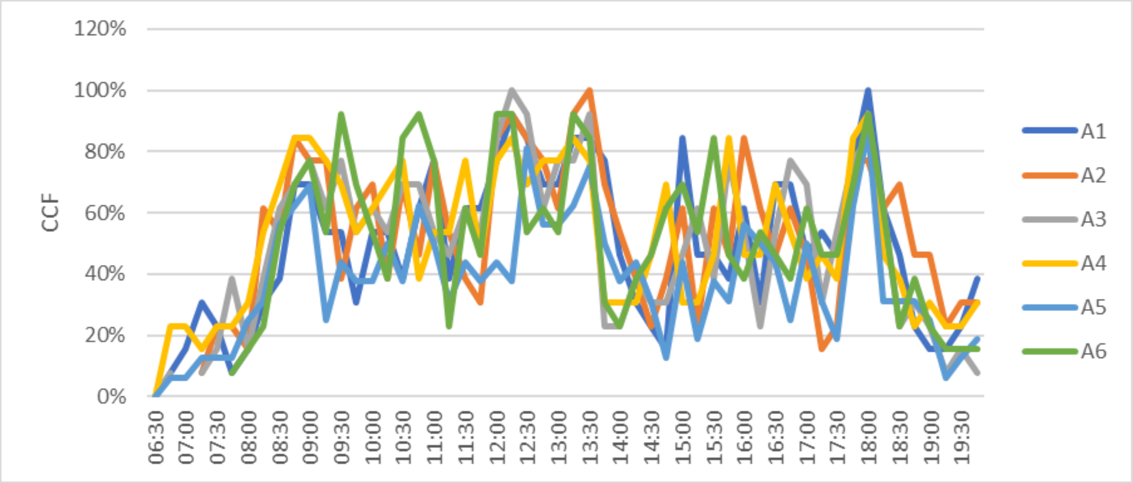

**Figure 1 Office A maximum car capacity factors for each 15-minute period**

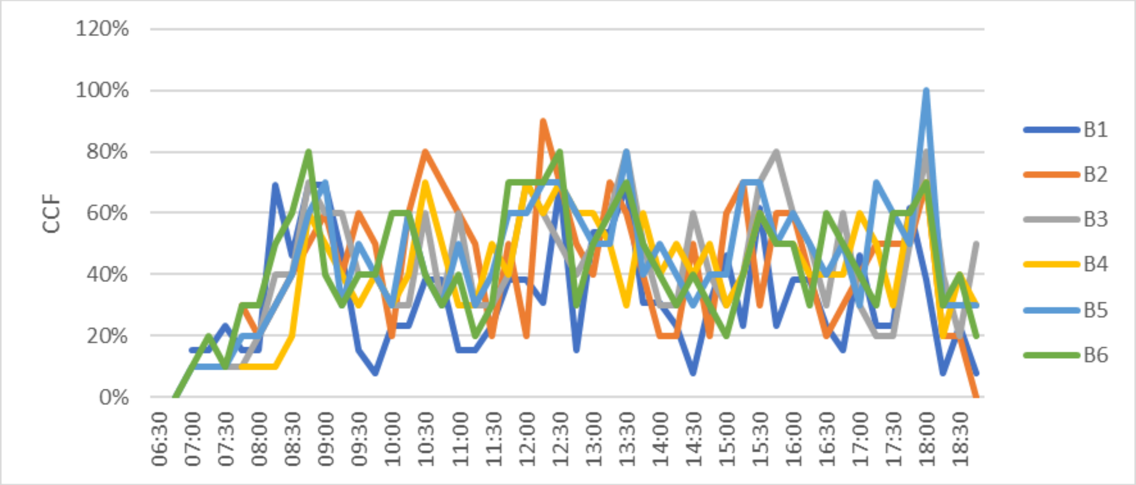

**Figure 2 Office B maximum car capacity factors for each 15-minute period**

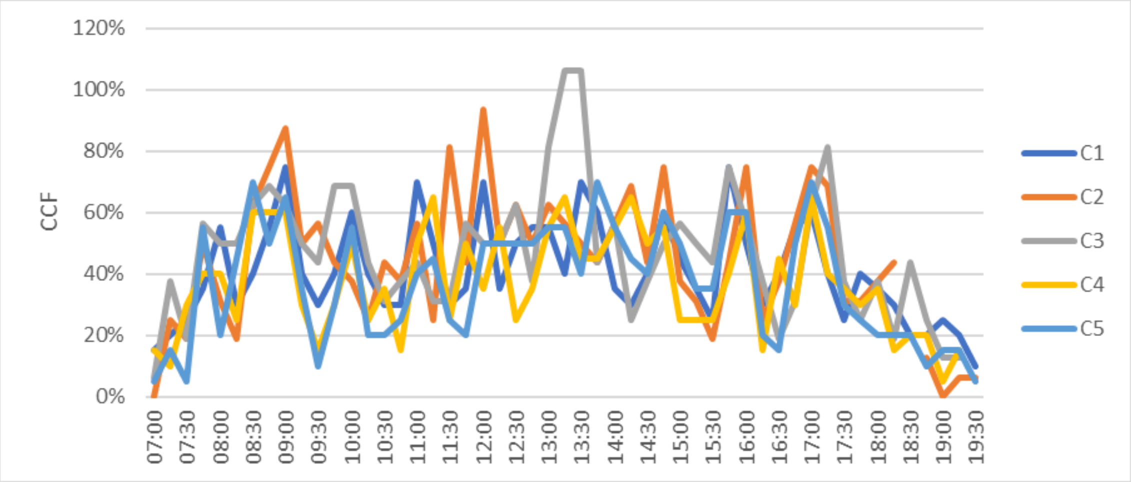

Figure 3 Office C maximum car capacity factors for each 15-minute periods

## 5 THE EFFECT OF CAR SIZE ON CAR CAPACITY FACTORS

Fig. 4, 5 and 6 show car capacity factors for different rated loads for 15-minute periods of a day. The values represent averages across the maximums of lifts with the same rated load and measurement days. The figures also present handling capacity ratios, to which observed car capacity factors seem to be related. It is worth noticing that the 15-minute periods and the averaging smooth the peak values from the previously shown values.

In each office, the larger cars have clearly lower car capacity factors compared to the smaller cars. This observation confirms the known effect of safety standards on available car area, but the posed limits are not necessarily the only reasons. If a lift group contains lifts with different sizes and especially if they look equally narrow, passengers do not necessarily realize the additional space in the larger lifts.

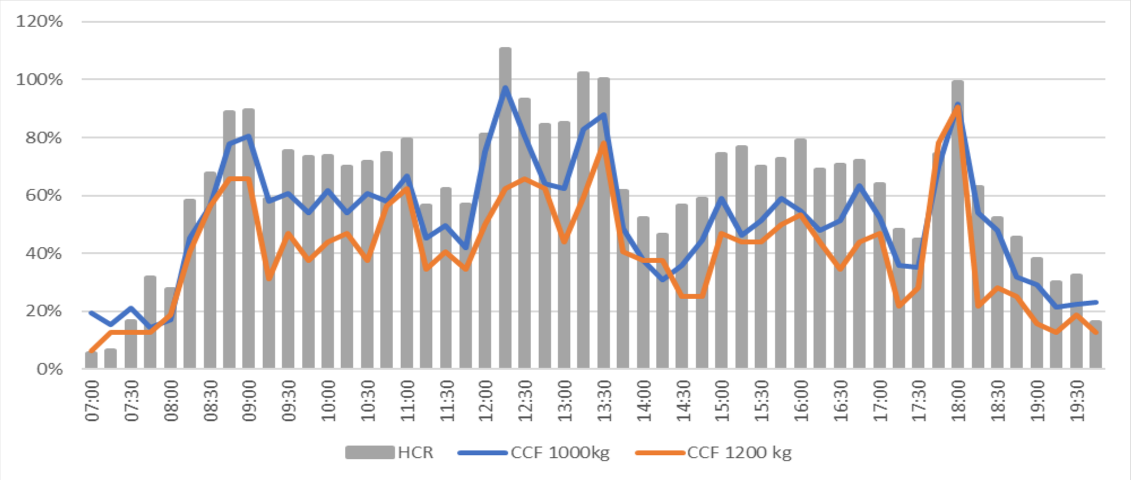

Figure 4 Average of maximum car capacity factors for 1000 kg and 1200 kg lifts in Office A

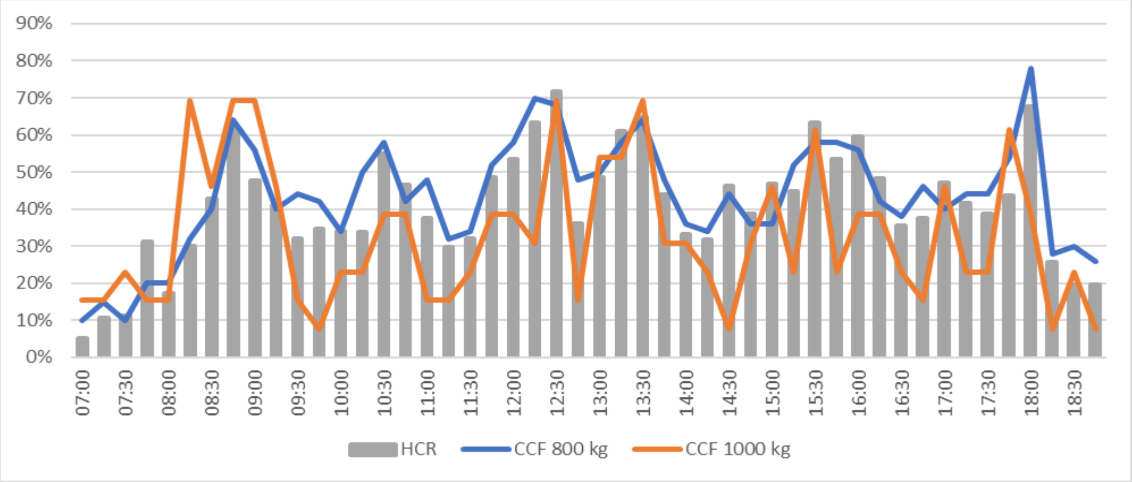

**Figure 5 Average of maximum car capacity factors for 800 kg and 1000 kg lifts in Office B**

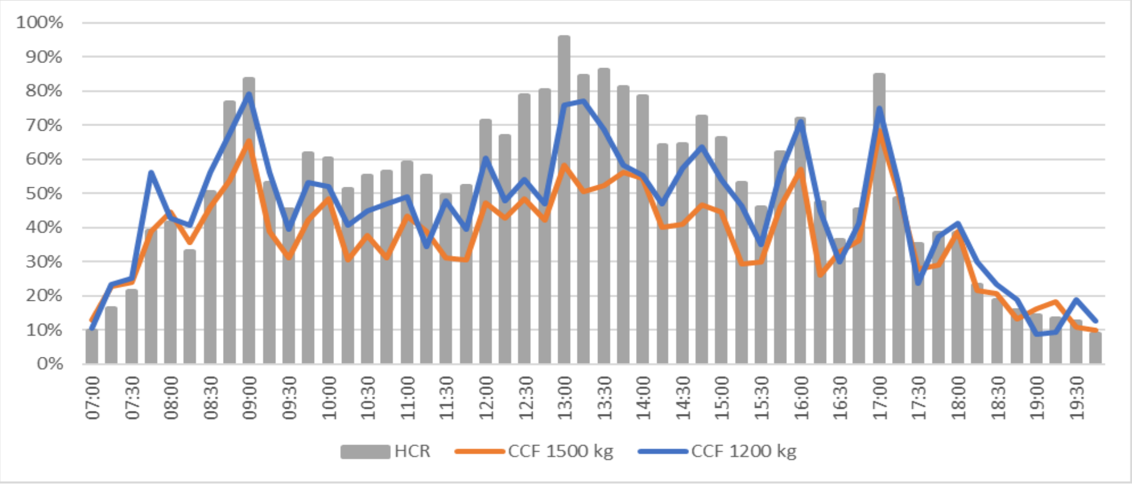

**Figure 6 Average of maximum car capacity factors for 1200 kg and 1500 kg lifts in Office C**

## 6 CONCLUSION

In this paper, the maximum number of passengers accepting to board a lift was studied in three office buildings. Sensor devices were installed in the lifts to automatically count and record the number of boarding and alighting passengers during each stop. Car capacity factors and handling capacity ratios were derived from the passenger counts for different times of a day. Car capacity factor was defined as the ratio of the maximum number of passengers in a lift to the rated passenger capacity. Handling capacity ratio, on the other hand, relates passenger demand within a period to lift group handling capacity. These quantities help in normalizing observations across different factors such as region, cultural background, city, neighbourhood, building, tenant, time of day and lift type.

The results show that passengers repeatedly boarded lifts until car capacity factor reached about 80%, which roughly corresponded to an area of 0.21 $m^2$ per passenger. These values could be used as safe defaults when defining passenger capacity in lift traffic design at least in Europe. However, lifts were also filled up to their rated passenger capacities, which may be acceptable in some regions. Furthermore, passengers also accepted higher densities in lifts during midday lunch-peak and evening downpeak compared to morning uppeak. Therefore, local rather than global guidance on defining passenger capacity should be sought during the design process to ensure that the lifts can comfortably accommodate the assumed number of passengers and the size of the lift installation does not become excessive.

At least one lift in each studied group had higher rated load compared to the others. An important finding was that the larger lifts of the groups were consistently loaded to lower car capacity factors than the smaller ones. This result may arise from available car areas per passenger in fully loaded cars. Alternatively, passengers may not be able to recognize the additional space in the larger cars if the cars are narrow and about equal in width. This raises a doubt whether lift traffic design should be conducted according to the smallest car size of a group. Such a precaution may not be necessary if the larger cars are also wider than the smaller ones but may be necessary in the case of equal car widths.

Ideally, lift traffic design is based on realistic assumptions on lift passenger behaviour. Data analysis as shown in this paper can be used to derive passenger capacities but should be extended to a wider range of geographical areas and building types. The data analysis should be accompanied with behavioural observations, which could reveal the reasons and conditions why passengers accept or refuse to board a lift. Such results could help developing lift traffic simulation models further. Since the used in-car sensors cannot detect passengers in lift lobbies, lobby sensors could complement the data acquired with the in-car sensors.

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## BIOGRAPHICAL DETAILS

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