Human Body Size in Lift Traffic Design

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Abstract. Calculations and simulations in lift traffic design assume a certain passenger capacity of a lift, i.e. the maximum number of passengers the lift can accommodate. Industry standards define the passenger capacity by dividing the rated load of a lift by the average weight of a passenger. An alternative approach divides the car area by the area of a body ellipse, which models the space requirement of a passenger. Lift safety standards assume a significantly smaller area per passenger than the typical body ellipse. This implies that area-based passenger capacity is smaller than load-based, and, therefore, also the lift group handling capacity becomes smaller. This paper reviews statistics of human body dimensions from existing literature. Body ellipses drawn from the dimension distributions as well as the typical body ellipse are used to study how many passengers fit in standard-sized lifts. Traditionally, lift group service quality has been evaluated by passenger waiting time and time to destination. This paper proposes a new service quality metric for the area available to passengers. Body sizes vary from one country to the next, in different kinds of buildings, as well as they evolve over the course of time. Therefore, the definition of passenger capacity as well as adequate space for comfortable travel needs to be periodically redefined according to local practices.

1 INTRODUCTION

Lift traffic analysis is based on passenger capacity, which is the maximum number of passengers a lift car can accommodate. Industry standards define passenger capacity by dividing the rated load of a lift by the average passenger weight, which is, for example, 75 kg in Europe [1], 72.5 kg in the US [2], and 67 kg in Japan [3]. Thus, a particular rated load results in different passenger capacities depending on the standard. EN 81-1 also defines the minimum and maximum available car area for each rated load to prevent overloading of the car. The available car area per passenger decreases as the rated load increases. For example, the area per passenger in a 100 kg (one person) lift is at least 0.28 m^2 and at most 0.37 m^2 but in a 1600 kg (21 persons) lift it is 0.155 m^2 and 0.170 m^2 [1].

An alternative approach defines passenger capacity as the maximum allowed area of a lift divided by the 0.21 m^2 occupancy area of a passenger weighing 75 kg [4]. The area of a passenger is taken as the area of the Fruin body ellipse with width 600 mm and depth 450 mm, which includes an additional 20 mm space in width and 120 mm in depth [5]. However, the Fruin body ellipse was derived for a large 95th percentile male with respect to maximum body breadth and depth [6, 7], but the 95th percentile weight was in the 1950s about 90 kg [8]. Since it is highly unlikely that only men of such size wait for a lift at the same time, also the area-based passenger capacity should be defined with the average passenger dimensions rather than the 95th percentile dimensions. The surveys reported average weight 73 kg [8] as well as body breadth 530 mm and depth 290 mm [6]. The area of a body ellipse according to these dimensions and the additional space becomes 0.177 m^2. Then, the passenger capacity of a 1600 kg lift becomes 20.1 passengers with 0.177 m^2 occupancy area instead of 16.9 passengers with 0.21 m^2 occupancy area [9].

The body size distribution of the target population using the lifts depends on the gender as well as the building type and its geographical location. In general, office buildings are occupied by adults but hotels and residential buildings by children, adults and elderly people. In the Far East, people are smaller in size compared to western countries. This paper studies how many passengers a lift can physically accommodate and proposes a new service quality metric for the space available to the passengers, which overcomes the pitfalls of area-based definition of passenger capacity.

2 HUMAN FACTORS AFFECTING LIFT TRAFFIC DESIGN

Maximum body breadth and depth are commonly called clearance dimensions [7]. Still to date, the distributions of these dimensions for males originate from a survey conducted by the US Air Force in the 1950s, according to which the 95th percentile maximum body breadth and depth were 580 mm and 330 mm, respectively [6]. These 95th percentile clearance dimensions were the basis of the Fruin body ellipse, which contains 20 mm additional space in width and 120 mm in depth for clothing and personal space [5]. On the other hand, Pheasant body ellipse was defined for designing workspaces and taking into account ergonomics by adding 50 mm both in width and depth to the 95th percentile clearance dimensions [7]. The areas of the Fruin and the Pheasant body ellipses are 0.212 m^2 and 0.189 m^2, respectively. Thus, even though they are based on the same clearance dimensions of the 95th percentile male, their areas differ clearly due to different requirements for the space around the body.

The clearance dimensions have not been measured since the original US Air Force survey, but several surveys report statistics on shoulder breadths [7, 8] and waist circumferences [8, 10, 11]. In addition, the Air Force surveys [6, 8] summarize measurements of relatively young males of an average age of under 30 years who were fitter than the general population [10, 11]. In comparison, the median (95th percentile) waist circumference was 80.5 cm (95.2 cm) in the Air Force survey [8] while the 1960s' survey of the general population reported a median 88.3 cm (95th percentile 109.0 cm) for males aged 18-79 years, 79.2 cm (99.8 cm) for males aged 18-24 years, and 85.6 cm (105.7 cm) for males aged 25-34 years [10]. Thus, males of age between 18 and 24 years in the general population corresponded closely to the Air Force personnel at that time. On the other hand, overweight and obesity have become more and more common in western countries. In the US, a recent survey indicates that the median (95th percentile) waist circumference among males has increased to 99.4 cm (128.1 cm) [11], thus 10 cm increase in the median and 20 cm increase in the 95th percentile compared to the data of the 1960s.

Table 1. 95th percentile points of body dimensions in some countries [7]

Country	Shoulder breadth [mm]		Chest depth [mm]		Abdominal depth [mm]	
	Men	Women	Men	Women	Men	Women
Brazil	490	N/A	275	N/A	305	N/A
France	515	470	280	295	320	305
Hong Kong	470	435	235	270	270	280
India	440	N/A	205	N/A	235	N/A
Japan	475	395	230	235	255	240
The Netherlands	520	445	330	350	375	360
Poland	475	410	275	285	310	295
Sri Lanka	400	360	205	210	235	220
Sweden	510	425	255	300	290	310
United Kingdom	510	435	285	295	325	305
United States	515	440	290	300	330	310

Body sizes also vary a lot between geographical areas. Table 1 shows the 95th percentile shoulder breadth, chest depth and abdominal depth in different countries [7]. In the western countries, shoulder breadths of men vary from 510 to 520 mm but, for example, abdominal depths have greater differences, from 290 to 375 mm. On the other hand, Asians are clearly smaller in size compared to westerners. As extremes, the area of the body ellipse[1] of Dutch men equals 0.153 m^2, but the area of Sri Lankan workers is only 0.074 m^2. These are considerably smaller than the areas of the Fruin and the Pheasant body ellipses.

The maximum number of passengers that actually pack into a lift depends not only on body sizes but also on human behaviour. People prefer to keep a distance from one another within the personal space around them [12]. The desire for personal space (probably) explains the observation that lifts are not packed more than 63-76% of the load-based passenger capacity [13]. For example, if a 1600 kg (21 persons, 3.56 m^2) lift is loaded within this range, the number of passengers inside the lift ranges from 13 to 16 passengers and the area per passenger from 0.223 to 0.274 m^2. This corresponds to comfortable loading, where passengers do not cross the touch-zone of others and the available area per passenger equals 0.279 m^2 [5].

Also passengers' motivations affect their decisions whether to board a lift or not. According to an old experiment, test persons comprising only women packed in a lift as tightly as 0.139 m^2 per person, and a mixed group of men and women achieved 0.167 m^2 per person [5]. If the passengers know each other or they are leaving an office building in the evening, lifts have been observed to carry so many passengers that the available area reduces to 0.14 m^2 per person [10]. A tight social group (a family, a couple) prefers to keep together: either the group does not board if the available space is not sufficient for all members, or the last member to board pushes in even if the lift is already crowded. At football stadiums in the UK, extreme crowd densities have been observed during the ingress to the stadium (0.125 m^2 per person) and during overcrowding eventually leading to a disaster (0.1 m^2 per person) [14]. Thus, even an uncomfortably small personal space is tolerated for a while if there is a good reason behind it.

3 FITTING BODY ELLIPSES IN A LIFT CAR

The problem of finding the maximum number of passengers that a lift can accommodate is modelled as a 2-dimensional packing problem which aims to determine the maximum number of body ellipses that can be packed within a rectangle. *The Ellipse Packing Problem* (*EPP*) is solved by applying an iterative algorithm, where, in each iteration, first *the Ellipse Feasibility Problem* (*EFP*) checks whether all the ellipses fit within the rectangle and do not cross their boundaries, then the number of ellipses is increased by one and the next iteration is carried out. If a feasible solution is not found in the current iteration, the algorithm terminates and the optimal solution to the EPP is the last feasible set of ellipses.

The EFP is formulated as a nonlinear programming problem where its optimal value equals zero if it exists. Let E denote the set of ellipses and W the set of walls of the lift car. Define $EEO(e, f)$ to be the overlapping area of ellipses e and f, and $WEO(e, w)$ to be the overlapping area of ellipse e and wall w. With this notation, the EFP can be written as follows:

$$\min \sum_{e,f \in E | e \neq f} EEO(e, f) + \sum_{e \in E, w \in W} WEO(e, w) \tag{1}$$

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[1] These body ellipses are calculated from the 95th percentile shoulder breadth (bideltoid) and the larger one of chest and abdominal depth without any additional space around.

The problem involves three decision variables for each ellipse: one for rotation, which determines the angle between the ellipse major axis and x-axis, and two for translation, which determine the x- and y-coordinate of the ellipse centre point. Successive quadratic programming is applied to solve the problem. The overlapping areas are calculated by the method presented in [15].

The numerical experiments consider general-purpose lifts of ISO 4190-1 [16], whose rated loads (*RL*), widths (*B*) and depths (*D*) are given in Table 2. The table also shows the *Passenger Capacity* (*PC*), the internal *Car Area* (*CA*), the *Car Load Factor* (*CLF*), and the *Area Per Passenger* (*APP*), which are derived as follows by assuming that a passenger weighs 75 kg on average and denoting the number of passengers by *P*:

$$PC = RL/75\,, \tag{2}$$

$$CA = B \times D\,, \tag{3}$$

$$CLF = P/PC \times 100\%\,, \tag{4}$$

$$APP = \frac{CA}{CLF \times PC}\,. \tag{5}$$

Table 2. Car dimensions, passenger capacities, car areas calculated from the ISO 4190-1 dimensions and the average areas per passenger with 100% car load factor

RL [kg] ISO 4190-1	B [mm] ISO 4190-1	D [mm] ISO 4190-1	PC [N] EN 81-1	CA [m^2] ISO 4190-1	APP [m^2]
800	1350	1400	10	1.89	0.189
1000	1600	1400	13	2.24	0.172
1275	2000	1400	17	2.8	0.165
1600	2100	1600	21	3.36	0.160
1800	2350	1600	24	3.76	0.157
2000	2350	1700	26	3.995	0.154

First, the largest body ellipse dimensions that still fit in a 2000 kg lift are sought for a fixed number of identical passengers. The number of passengers is varied so that the corresponding car load factor varies from 50 to 100% in 10% steps. The aspect ratio of the ellipses is set to 1.82, which is the average ratio of the maximum body breadth to the maximum body depth for the 5th, 50th, and 95th percentile points for men [7]. Table 3 presents the dimensions of the largest ellipses found for each car load factor and their areas. The area utilization percentage gives the total area of all the ellipses divided by the car area, the maximum utilization being equal to 84.6%. Since the 2000 kg lift has the smallest area per passenger, these results show that all lifts of Table 2 can be fully loaded with identical passengers if their body ellipses occupy at most 0.130 m^2.

Next, the maximum number of passengers that fit in the lifts of Table 2 is determined by considering several compositions of passenger groups with different body sizes. The dimensions of each passenger group are given in Table 4. The first passenger group consists of identical males with the Fruin body ellipse. The second passenger group models identical females and is obtained from the 95th percentile point of the clearance dimensions [7] with an additional 15 mm width and

125 mm depth (to obtain good round values). The last two passenger groups represent males and females with body ellipse sizes drawn randomly. The widths of these ellipses follow the normal distributions of the male and female maximum body breadths with the averages of 530 mm and 420 mm, respectively [7]. The aspect ratios between the body width and depth are 1.82 for males and 1.53 for females. The width and depth are also increased by 20 mm to allow some space for clothing, which is twice the recommended 10 mm correction for indoor clothing but half of the recommended 40 mm correction for heavy outdoor clothing [7]. This assumption models the situation where passengers are under pressure of packing the lift and smaller-than-usual personal space can be tolerated.

Table 3. The largest possible ellipse sizes for given car load factors in a 2000 kg lift

CLF [%]	Passengers [N]	Ellipse Width [mm]	Ellipse Depth [mm]	Ellipse area [m^2]	Area utilization [%]
50	13	776	426.4	0.266	84.6
60	15	714	392.3	0.220	82.6
70	18	655	359.9	0.185	83.3
80	20	619	340.1	0.165	82.6
90	23	580	318.7	0.145	83.5
100	26	549	301.6	0.130	84.6

Table 4. Axis lengths and average area of body ellipses for each passenger group

Passenger group	Ellipse Width [mm]	Ellipse Depth [mm]	Ellipse Area [m^2]
Male-95	600	450	0.212
Female-95	500	450	0.177
Male-Gaussian	$\sim N(530, 30) + 20$	Width / 1.82 + 20	0.130
Female-Gaussian	$\sim N(420, 40) + 20$	Width / 1.53 + 20	0.099

Four scenarios combine the above passenger groups differently. In *Male-95* and *Female-95* scenarios, all passengers are identical 95th percentile males and females from the corresponding passenger groups. The *Mixed-95* scenario consists of passengers from the Male-95 and Female-95 groups so that there is an equal number of males and females. In the *Mixed-Gaussian* scenario, male and female passengers are randomly selected from the respective normal distributions with a passenger having an equal probability of being male or female. The scenarios are solved for the lifts specified in Table 2. The Mixed-Gaussian scenario is solved ten times with redrawn random samples for the ellipse widths and average values are reported instead of individual runs. Figure 1 shows the distributions for the male and female ellipse widths and individual random samples drawn for a 2000 kg lift.

Figure 2 shows the maximum number of passengers that fits in the lifts in the different scenarios. From the figure one can observe that the maximum number of passengers that can be loaded follows a linear trend with dependency on the rated load and the body ellipse size. The lifts can accommodate full load only in the Mixed-Gaussian scenario, i.e. when the ellipse widths are drawn randomly from the normal distributions and passengers are males or females with equal probability.

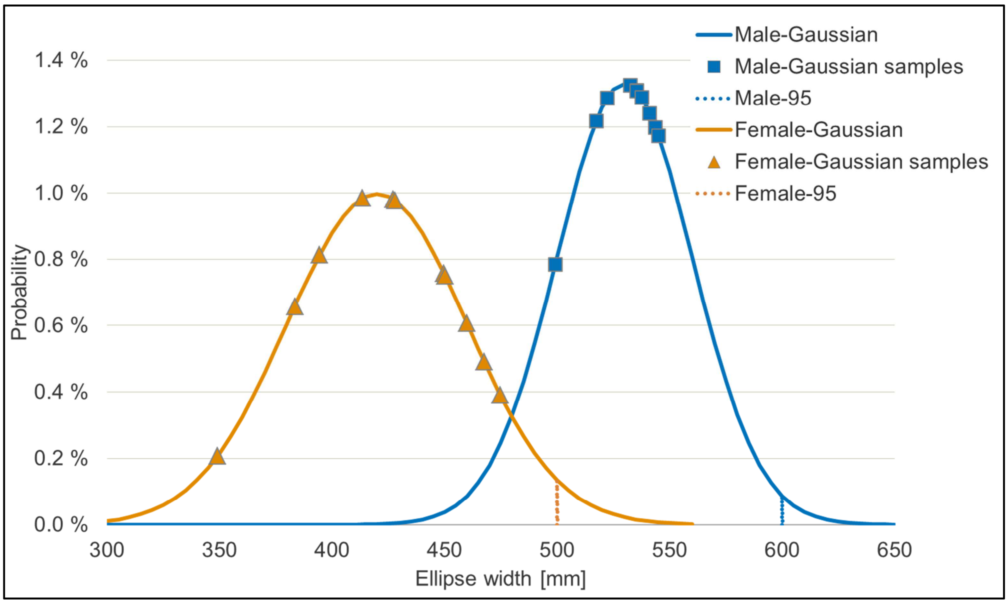

Figure 1. Mixed-Gaussian and 95th percentile ellipse widths

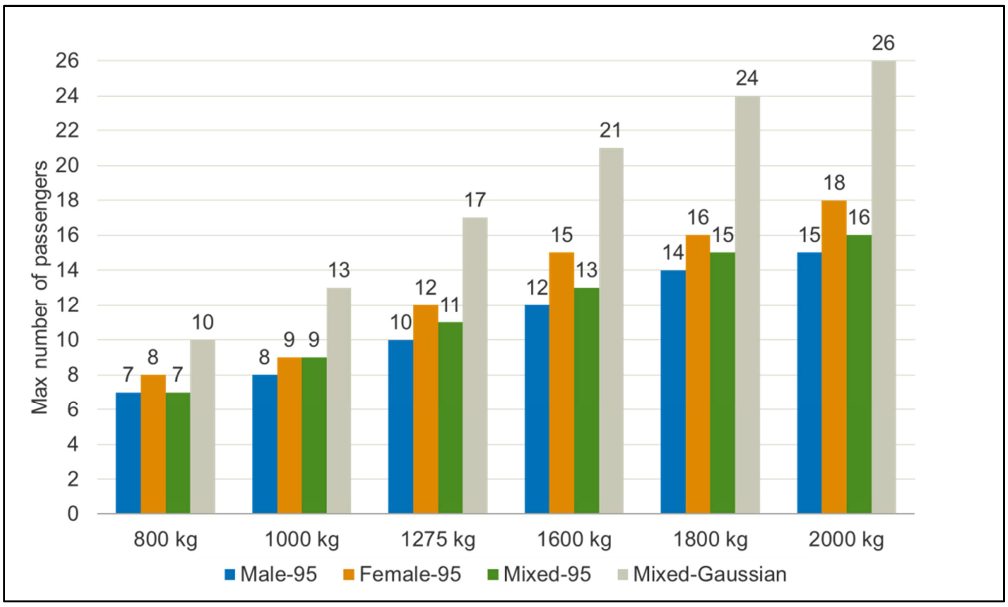

Figure 2. Maximum number of passengers that fit in the lifts

Table 5 gives the maximum car load factors for the scenarios. In the Male-95 scenario, the car load factor is as low as 57.1% for the 1600 kg lift. It is also worthwhile noticing that the maximum number of passengers in this scenario is always notably less than the area-based passenger capacity [4, 9] although the body ellipses have the same area. The difference occurs because the car area is not fully utilized. In the Mixed-Gaussian scenario, cars can be fully loaded. Table 6 presents the average available areas per passenger. The scenarios consisting of 95th percentile males and females have the average area per passenger in the range of comfortable densities. However, the available areas with the Mixed-Gaussian passengers are well below 0.2 m^2 per passenger but still clearly above the average body ellipse sizes 0.130 m^2 of men and 0.099 m^2 of women.

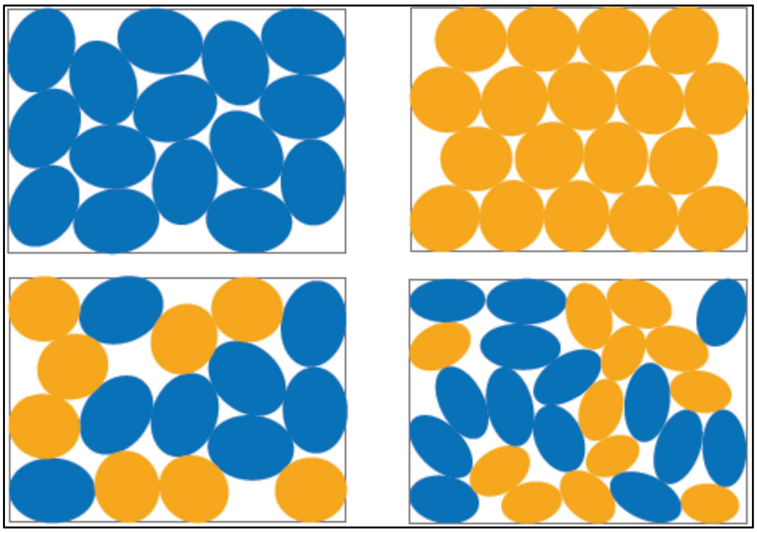

Figure 3: Solutions with different body ellipse scenarios for the 2000 kg lift. Top left: 15 Male-95 ellipses; top right: 18 Female-95 ellipses; bottom left: 8 Male-95 ellipses and 8 Female-95 ellipses; bottom right: 14 Male-Gaussian ellipses and 12 Female-Gaussian ellipses.

Table 5: Car load factors based on the maximum number of passengers

Scenario	Car Load Factor [%]					
	800 kg	**1000 kg**	**1275 kg**	**1600 kg**	**1800 kg**	**2000 kg**
Male-95	70.0	61.5	58.8	57.1	58.3	57.7
Female-95	90.0	76.9	76.5	71.4	70.8	73.1
Mixed-95	80.0	69.2	70.6	66.7	62.5	61.5
Mixed-Gaussian	100.0	100.0	100.0	100.0	100.0	100.0

Table 6: Available area per passenger based on the maximum number of passengers

Scenario	Area per passenger [m^2]					
	800 kg	**1000 kg**	**1275 kg**	**1600 kg**	**1800 kg**	**2000 kg**
Male-95	0.270	0.280	0.280	0.280	0.269	0.266
Female-95	0.270	0.249	0.233	0.240	0.235	0.222
Mixed-95	0.270	0.249	0.255	0.258	0.251	0.250
Mixed-Gaussian	0.189	0.172	0.165	0.160	0.157	0.154

4 LEVEL OF SERVICE IN A LIFT CAR

Traditionally, the lift group handling capacity is defined with 80% average car load of the load-based passenger capacity, which implicitly assumes that sometimes the lifts are occupied up to 100% of their capacity. As shown, 100% loading is physically possible when considering a realistic distribution of human body dimensions and mixture of men and women. Thus, the assumption of 100% loading in theoretical calculations and simulations remains valid.

In practice, only up to 76% loading has been observed [13], which is (probably) caused by passengers' desire for personal space. The traditional way of conducting lift traffic design calculations and simulations does not take into account the area occupied by a passenger but that is easily overcome by considering area per passenger as a new design metric.

The value of area per passenger is calculated using the average car load factor as in Eq. 5, which defines the number of passengers for the up-peak equations and is readily available as a simulation statistic [17]. Then, the area per passenger is compared with the Fruin Level of Service (LOS) ranges for queuing areas, of which LOS E is given as an example for lift occupancy [5]. As shown in Table 7, the lower limit of LOS E occupancy (0.2 m^2 per passenger) corresponds to 80% (or greater) car load factor for rated loads up to 1600 kg. For 1800 kg or 2000 kg lifts, 77-78% car load factor result in area per passenger within LOS E lower limit. Thus, the usual way of defining maximum handling capacity with the average car load factor 80% is in line with LOS E. On the other hand, occupancy of 0.3 m^2 per passenger on the upper limit of LOS E occurs with car load factors between 55% and 60%, which can be considered as a good target value for comfortable travel.

Table 7. Area per passenger, LOS with increasing car load factor and LOS ranges [5]. APP calculated using load-based passenger capacity (Eq. 2) and car areas as in Table 2.

CLF [%]	Area per passenger [m^2] and LOS					
	800 kg	1000 kg	1275 kg	1600 kg	1800 kg	2000 kg
10	1.890	1.723	1.647	1.600	1.567	1.537
20	0.945	0.862	0.824	0.800	0.783	0.768
40	0.473	0.431	0.412	0.400	0.392	0.384
60	0.315	0.287	0.275	0.267	0.261	0.256
80	0.236	0.215	0.206	0.200	0.196	0.192
100	0.189	0.172	0.165	0.160	0.157	0.154

LOS	APP [m^2]
A	≥1.2
B	0.9-1.2
C	0.7-0.9
D	0.3-0.7
E	0.2-0.3
F	< 0.2

The use of LOS does not change the traditional way of conducting lift traffic calculations and simulations. Thus, the definition of the passenger capacity remains load-based according to the applicable local standard. LOS involves only the calculation of the area per passenger and its classification as an extra work using car load factor and car area. However, the area per passenger is a rather abstract concept, but it could be visualized by schematic drawings [5] or by 3D visualization of traffic simulation [18].

5 DISCUSSION

The load-based passenger capacity accompanied with the area per passenger as a service quality metric has many advantages over the area-based capacity. Firstly, new lift traffic designs with the area-based passenger capacity are not in line with the old ones conducted with the load-based passenger capacity since area-based passenger capacity is 58-90% of load-based passenger capacity [4]. Also the lift group handling capacity decreases by the same ratio just because of the definition of passenger capacity changes. When keeping the traditional load-based passenger capacity intact, new designs can be compared directly to old ones while the area per passenger brings additional information about the suitability of the design.

Since passenger capacity is the determinant of the traffic design calculations, the assumed body ellipse area affects directly the results of the analysis. Therefore, the occupancy area should represent an average user of the target building type, geographical area, and culture. The definition of area-based passenger capacity is based on the occupancy area 0.21 m^2 per passenger weighing 75 kg [4, 9], which is the area of the Fruin body ellipse [5]. However, the Fruin body ellipse was derived for 95th percentile male dimensions, which corresponds to about 90 kg man and is not in line with the previous assumption. In addition, the body ellipse contains 0.06 m^2 additional space around the body. Thus, the area-based passenger capacity hides the assumptions behind it without proper documentation, which is not the case for the load-based passenger capacity. In addition, area per passenger does not depend on the choice of average passenger occupancy area, and, therefore, it is independent of culture, geographical area, and building type.

Since lift traffic calculations and simulations are based on mathematical theories, complex relationships, and many technical parameters, the rationale and effect of area-based passenger capacity remains hidden from and incomprehensible to the decision maker. Then, the designer is responsible for the validity of the design assumptions and the decision maker is (probably) neither able to challenge them nor provide insights of the target occupants. If the lift traffic analysis shows the area per passenger as well as the LOS classification, the decision maker and the designer may enter the debate whether the proposed solution is adequate for the building under consideration. Thus, the decision maker is able to make an informed decision based on his/her assessment on all aspects of the lift passenger service.

The standards allow some variation in car dimensions, which results in different internal car areas and therefore area-based passenger capacities. In addition, the lift manufacturers may have their own dimensions within the limits of the standards. Thus, the designer cannot know the true dimensions of the car before the lift supplier is chosen for the project, and therefore, the calculations with area-based passenger capacity are not necessarily correct. Furthermore, the car area available to the passengers may be further reduced from the standard due to car shape, hand rails, and decoration, the effect of which may or may not be known to the designer during the building design phase. Thus, even a small change in the available car area may change the area-based passenger capacity and, therefore, also invalidate the conducted analysis. The use of load-based passenger capacity and area per passenger does not completely eliminate the effect of non-unique car areas. However, the change in car area does not require a re-run of the whole analysis, only re-evaluation of area per passenger is needed. Since the range of LOS E is quite wide, a small change in the car area does not necessarily imply a notable change in the area per passenger.

6 CONCLUSION

This article studied human body sizes and how they could be taken into account in lift traffic design. The motivation for this study arises from the two definitions of passenger capacity, which is the maximum number of passengers a lift car can accommodate. Current lift safety standards define the passenger capacity by dividing lift rated load by the average passenger weight, which is in Europe 75 kg. In an alternative approach, the maximum allowed car area is divided by the 0.21 m^2 body ellipse area of a passenger weighing 75 kg. Of these two definitions, the area-based gives much smaller passenger capacity than the load-based, which creates unnecessary confusion among the practitioners.

When studying the maximum loading of lifts, it was found that the standard-sized lifts can be loaded up to 100% of the load-based passenger capacity. Full load was achieved when lifts with different rated loads were packed with body ellipses drawn randomly from body dimension distributions of men and women. This shows that the maximum car occupancy in lift traffic design should be 100% of the load-based passenger capacity. Thus, the real-world observation that a lift is not loaded up to 100% must be the consequence of human behaviour and preferences. Therefore, the available space for passengers should not be treated as a matter of capacity.

Since personal space in a lift is an important factor in comfortable travelling, it should be considered explicitly in lift traffic design. The Level of Service concept developed by Fruin can be applied to lifts since the design calculations and simulations have readily available the average number of passengers in the lift. Then, it is possible to calculate the average area per passenger and classify it according to the existing Level of Service definitions for queuing areas. Fruin recommended lifts to be the only application of LOS E with 0.2-0.3 m^2 area per passenger. Coincidental or not, 80% average car load, which has been used for a long time to define the maximum handling capacity of a lift group, corresponds to the LOS E for lifts up to 1600 kg rated load. Therefore, the use of 80% car load factor in lift traffic design seems to be a valid approach. The consideration of exact area per passenger offers a way of defining target car load factor for large lifts of 1800 kg or greater, or a requirement for a more spacious solution than provided with 80% car load factor.

The advantage of using LOS and area per passenger over the area-based passenger capacity is based on its independence of building type, geographical area, culture, and differences in body sizes. Therefore, lift traffic design should be carried out in the traditional way by using the load-based passenger capacity to determine service quantity and area per passenger as an additional selection criterion for service quality. This provides a straightforward way to settle the conflict between the load- and area-based passenger capacities and keep the future traffic designs in line with the old ones.

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BIOGRAPHICAL DETAILS

Janne Sorsa graduated in Engineering Mathematics from Helsinki University of Technology in 2002. He joined KONE in 2001 and has been working for R&D and Major Projects. Currently, he holds the position of Manager of People Flow Planning. He has lectured on optimization algorithms and is currently finalizing his doctoral thesis at Aalto University.

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