In-depth Study on RTT-HC-MTT Relationship for Passenger Demand beyond Elevator Contract Capacity by Simulation

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Abstract. The traditional elevator system design practice is to calculate the round trip time (RTT) and associated parameters of pure incoming traffic during uppeak, followed by real-time computer simulation. Recent studies indicated that the normal traffic is much more complicated, consisting of a mixture of incoming, outgoing and interfloor patterns. The Universal RTT, under such complicated traffic patterns, was analytically developed eight years ago based on the concept of an appropriate origin-destination matrix describing the passenger transit probability and verified by Monte Carlo simulation. That model is based on the assumption that the total number of passengers demanding service within one round trip is limited to the elevator contract capacity, which is in line with the traditional uppeak incoming RTT formula. The idea of extending the consideration beyond the contract capacity was initiated two years ago. In this article, an in-depth study on such consideration is carried out so that the performance such as RTT, handling capacity (HC) and mean transit time (MTT) etc. under different traffic patterns is evaluated and analyzed with the help of Monte Carlo simulation. This article may help designers optimally size an elevator system during the RTT calculation stage without oversizing it if the prevalent traffic patterns of the building are known.

Elevator system designers, according to ISO 8100:32:2020 and CIBSE Guide D: 2020, are recommended to carry out calculation of the RTT and related parameters before any real-time computer simulation. This practice has been accepted by the elevator industry for a long time. However, conventional RTT evaluation normally considers a pure incoming traffic during uppeak. The Universal RTT calculation method developed in 2014-15 [1-3] extended RTT evaluation to consider different traffic patterns, including intra-entrance, incoming, outgoing and interfloor etc. But the total number of passengers being handled within one round trip was limited to the rated capacity of the elevator car, which could from time to time oversize the system design. The consideration to extend it beyond the rated capacity was initiated. This article provides an in-depth study on such extension by considering different traffic patterns with the help of Monte Carlo simulation, aiming at a more optimal system design by RTT calculation.

Keywords: Elevators, Universal round trip time, Handling capacity, Transit time, Contract capacity, Monte Carlo simulation.

NOMENCLATURE

Symbol	Full Name	Symbol	Full Name	Symbol	Full Name
P	total number of passengers at all floors demanding service within one round trip	CC*	contract capacity of the elevator car = maximum number of passengers accommodated simultaneously	RTT	round trip time
t_v	single floor jump time of the elevator under rated speed	d_f	floor height	v	rated speed of the elevator
$t_f(1)$	single floor jump time of the elevator including acceleration and deceleration only	t_o	door opening time	t_c	door closing time
t_p	average passenger transfer time	t_{pre}	door pre-opening time	t_{sd}	start delay time
H	average highest reversal floor under a pure 1-floor incoming traffic condition	S	average number of stops under a pure 1-floor incoming traffic condition	$UPPINT$	average duration of interval under a pure 1- floor incoming traffic condition
U_i	population of the *i*th floor, $1 \leq i \leq N$	U	total population of the whole building	ATT	average transit time of a passenger under a pure 1-floor incoming traffic condition
AWT	average waiting time of a passenger under a pure 1-floor incoming traffic condition	ic	ratio of incoming traffic demand in percent	og	ratio of outgoing traffic demand in percent
if	ratio of interfloor traffic demand in percent	ie	ratio of traffic demand within the entrance/exit floor stack in percent, assumed zero in this paper	HC	handling capacity conventionally measured in % of total population, but in this article, passengers/round trip
B	number of floors of the entrance/exit floor stack	Y	number of floors of the occupant floor stack	N	total number of floors of the building = $B + Y$ in this paper
L	number of elevators serving the building			**PTPV**	passenger transition probability vector representing the probability of a passenger entering or leaving each floor
PDFOD	probability density function origin-destination which is a matrix representing the probability of passengers going from the *i*th floor to the *j*th floor	**CDFOD**	cumulative distribution function origin-destination which is the sum of probabilities of **PDF OD** from element (1,1) to element (*i*,*j*)	PUP, PDN	number of passengers in the up-journey of the round trip, number of passengers in the down-journey of the round trip
MTT	mean transit time which is the weighted average between *ATTUP* and *ATTDN* by the *PUP* and *PDN* respectively	$ATTUP$	average transit time a passenger takes during the up journey within a round trip	$ATTDN$	average transit time a passenger takes during the down-journey within a round trip

* For a formal definition of contract capacity which should be better given in terms of mass vs platform occupancy, one could refer to [4] and [5] (Section 3.7). However, in this simulation study, *CC* only refers to the maximum number of passengers that the simulated car can accommodate to facilitate the computation of *HC* which is measured in terms of the number of passengers being handled.

1 INTRODUCTION

Traditionally, the computation of the uppeak round trip time (*RTT*) is the starting point of each elevator design project and the target is in-coming traffic only. It means that all passengers are assumed to enter the building at the main terminal, usually the ground floor, from the street although some are from the parking floors either above the main terminal or at the basement. This situation usually happens in the morning, say around 8:00 to 8:30 am, at common office buildings when the whole building is rather vacant, and the rush hour just begins while occupants wait for elevator services at the lobby of the main terminal.

When one elevator car arrives at the main terminal, P (number of passengers demanding service within one round trip) $\leq CC$ (the contract capacity of the elevator car) passengers enter the car, and they make car calls for their destination floors. Here, P is equivalent to the total demand of one round trip. For pure incoming traffic, P cannot be larger than CC because almost all passengers enter the car on the same floor, i.e. the main terminal. However, when interfloor and outgoing traffic modes are also considered, P could be larger than CC, which is the main theme of this series of studies because not all P passengers enter the elevator car at the entrance floors. This phenomenon when $P > CC$ is only valid under one or both conditions, i.e.

i) the existence of multiple entrance floors in a building, and

ii) mixed traffic conditions.

Perhaps a simple example could explain the former case. If one or two out of the CC passengers entering the elevator car at the ground floor want to pick up their cars on the parking floors, i.e. still considered as entrance floors, they may leave the elevator car at the parking floors where one or more passengers waiting for services at these floors could enter the car and fill up the vacancies. Under this condition, $P > CC$ within that particular round trip.

As mentioned above, under a pure incoming traffic condition and classically, P obviously cannot go beyond CC. At the same time, S ($\leq P \wedge \leq N$) number of stops during the subsequent up-journey is made until the elevator car reaches the highest reversal floor, $H \leq N$ (which is the total number of floors served by the elevator bank above the main terminal). Since both S and H are statistical figures, they are normally non-integers by calculation but for each single round trip, both must be integers. At the Sth stop (excluding the first stop at the main terminal) and at the Hth floor, the elevator car becomes vacant, which will then make an express down-trip back to the main terminal. This completes a standard round trip with a well-defined *RTT*. Equation (1) is the standard equation used to estimate such *RTT*, based on Chapter 3 of [5].

$$RTT = 2H\frac{d_f}{v} + (S+1)\left(t_c + t_{sd} + t_f(1) + t_o - t_{pre} - \frac{d_f}{v}\right) + 2Pt_p \qquad \text{where} \tag{1}$$

H = average highest reversal floor; d_f = average interfloor height;

v = rated speed; S = average number of up-stops; t_c = door closing time;

t_{sd} = start delay time; $t_f(1)$ = single floor flight time; t_o = door opening time;

t_{pre} = pre-door opening time; P = average number of passengers inside the elevator;

t_p = average single passenger transfer time (entry or exit).

Under a general case where the floor population density is assumed non-uniform, S and H can be estimated by equation set (2) according to [6] (pp. 140-141). Here, U_i is the population of the ith floor and U the total population of the whole building under consideration. Actually, these two equations are also applicable to uniform population distribution as a special case by making all $U_i = U/N$. For equations (1) and (2) to be applicable, several assumptions have to be made.

i) Floor height is uniform and constant.

ii) Half the floor is used for acceleration and half for deceleration. In other words, a one-floor jump consists of acceleration and deceleration only.

iii) Passenger arrival rate is constant.

iv) Door opening and closing times must strictly follow the assigned values; no delay by any passenger is allowed.

Of course, suitable adjustments need to be made for them to be practical in the real world. However, for the purpose of traffic analysis and design by calculation, such simplification can reduce the burden on the calculation procedures, even when the Monte Carlo simulation is carried out. This is the format adopted throughout this article.

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

$$H = N - \sum_{j=1}^{N-1}\left(\sum_{i=1}^{j}\frac{U_i}{U}\right)^P \qquad (2)$$

$$\text{where } U = \sum_{i=1}^{N} U_i$$

Once the RTT has been estimated, the next step is to estimate the uppeak interval, $UPPINT$, the handling capacity, HC (conventionally represented in percent of total population of the building, but in this paper, it refers to number of passengers that can be handled by one elevator within one round trip) of a group of L elevators, the average waiting time [6] (page 120), AWT, and the average transit time [7], ATT, of passengers under such uppeak traffic condition by using equation set (3). The relationship between AWT and $UPPINT$ in equation set (3) may not be always reliable, in particular, when the demand is getting higher [8]. After all, on page 120 of [6], it is stated that equation (6.1) is just approximate.

$$UPPINT = \frac{RTT}{L} \quad ; \quad HC = \frac{300LP}{RTT}$$

$$AWT = \left[0.4 + \left(1.8\frac{P}{CC} - 0.77\right)^2\right]UPPINT \quad \text{for } 50\% \le \frac{P}{CC} \le 80\% \qquad (3)$$

$$\begin{aligned} ATT &= \frac{S+1}{2S}Ht_v + \frac{S+1}{2}\left(T - t_v\right) + Pt_p \\ &\approx 0.5Ht_v + 0.5S\left(T - t_v\right) + 1.5Pt_p \quad \text{quoted in } \textit{CIBSE Guide D } 2015 \end{aligned}$$

In practice, under very heavy traffic, P is very close to CC and then, the AWT could be approaching a very large value, as shown by Figure 6.1 [6] (page 121). According to the second equation on the first row of equation set (3), based on the required handling capacity of the building during a 5-minute uppeak period, the total number of elevators of the system, L, is determined. Of course, $P \leq CC$. At this point, the brief design has been completed; the next step recommended by the [9] is to carry out a real-time computer simulation to optimize different configurations.

This traditional process of traffic analysis by calculation has the following characteristics:

i) There are incoming passengers only who normally enter the building at the main terminal on the ground floor.

ii) A round trip normally begins at the main terminal and ends at the main terminal, which may not be the case if there are parking floors above or below the main terminal.

iii) The main issue is that only $P \leq CC$ number of passengers is considered within one round trip. Suppose the whole building is served by one elevator only and if $P > CC$, the remaining (P - CC) passengers have to wait for service during the next round trip of the elevator.

For (i), it has already been confirmed [10-13] that uppeak traffic is no longer the dominant traffic pattern in a modern office building. Furthermore, the lunch peak mainly consisting of mixed traffic patterns may be even worse, which is considered the main challenge to an elevator system [14-16]. It is customary nowadays to quantitatively describe the prevailing traffic in a modern high-rise building at any time as a mixture of simultaneous incoming, outgoing and interfloor traffic demands [3].

For (ii), a new definition of a typical round trip using the ring concept of a virtual round trip was proposed [17, 2], the detailed discussion of which is beyond the scope of this article. The concept of a virtual interval was first suggested by [17] where the round trip time is more generally defined as the time from the moment the elevator car starts up to the next time it starts up after two reversals. The concept was further strengthened by [2] with the introduction of the "sense of reversal". Having said that, this new definition has been adopted in the simulation processes discussed in this article.

For (iii), when pure incoming traffic is considered, it is obvious that the elevator car is loaded with P ($\leq CC$) number of passengers at the main terminal and some parking floors. Only these P passengers are served during that particular round trip. However, when outgoing and interfloor, in particular, passengers exist within that round trip, the total number of passengers served by the elevator car could be many more than CC. For example, CC number of passengers enters the elevator car at the ground floor and destinations of (CC - 1) passengers are identical, say 5/F which is an occupant floor. The remaining passenger's destination is the top floor, the Nth floor. When the car reaches 5/F, all (CC - 1) passengers leave and the car becomes almost vacant, except one passenger staying behind. Under this situation, the elevator can flexibly serve up-going passengers from 5/F until the (N - 1)th floor whenever there are some vacancies inside. On the Nth floor, the car becomes vacant again and it can flexibly serve down-going passengers from the Nth floor until the floor above the main terminal. Under this consideration, the elevator car has actually served many more than CC passengers during that particular round trip. The simulations that follow have shown that although the RTT may be very much lengthened, the HC can be significantly increased as well. So, if only $P \leq CC$ number of passengers can be served within one round trip, as in the traditional way of calculation, the handling capacity may be seriously underestimated. Then, L, the total number of elevators of the system, may be seriously over estimated or the system design is oversized.

The idea of estimating the *RTT* of a typical round trip under the situation when $P > CC$ was first proposed and studied by So [18]. In the following sections, the methodology is briefly described again for the sake of completeness. Details of the mathematics can be found in [18]. Results of detailed performance study under different traffic patterns by Monte Carlo simulation will then be discussed as the main contribution of this article.

2 THE ORIGIN-DESTINATION MATRIX

There are two types of floors within a building, namely the entrance/exit floors and the occupant floors. At entrance/exit floors, building occupants can either enter or leave the building. Entrance floors need not be contiguous. By occupant floors, building occupants stay there to work or stay. At the same time, occupant floors need not be contiguous. But normally, they are contiguous in practice. Then, four types of traffic are typical, namely

i) Inter-entrance/exit floor traffic means passengers travel within the entrance/exit floor zone. For example, a passenger enters the elevator at the ground floor and leaves it at the 3rd parking floor to pick up the car etc. The percentage of occurrence of such traffic is termed *ie*% which is usually assumed zero.

ii) Incoming traffic means passengers enter the building at the entrance/exit floors with their destinations at the occupant floors. This is the most conventional type of traffic considered in RTT analysis, which usually happens during the uppeak. The percentage of occurrence is termed *ic*%. Such *ic*% may further be divided and applied to different entrance floors. Usually, the proportion with the main terminal is higher.

iii) Outgoing traffic means passengers get into the elevator from occupant floors but leave the building at entrance/exit floors. This usually happens during the down peak. The percentage of occurrence is termed *og*%.

iv) Finally, passengers can travel between occupant floors, called interfloor traffic, termed *if*%.

It should be noted that $ie + ic + og + if = 100\%$. A typical example of the lunch time period is provided in Chapter 4 of [5] where the total 5-minute demand accounts for 13% of the overall building population with a mixture of 0% inter-entrance, 45% incoming, 45% outgoing and 10% interfloor. So, RTT calculation must consider a mixture of these three common types of traffic.

To study the universal *RTT*, either by calculation or by simulation, the first step is to create a passenger transition probability vector (**PTPV**). From this vector, the probability density function origin-destination (**PDFOD**) matrix can be produced [1-3, 16]. From **PDFOD**, the cumulative distribution frequency origin-destination matrix, **CDFOD** can be produced.

A typical building under study consists of *B* number of floors in the entrance/exit stack (including the main terminal at the bottom of the stack) and *Y* number of floors in the occupant stack, i.e. total number of floors served by the elevator in this building is equal to $N = B + Y$. The first floor is the main terminal at the ground floor, which is the lowest floor. This configuration, for the sake of computational convenience, is a bit different from that in the conventional *RTT* formula where the building has $(N + 1)$ floors. Here, the 1st floor is the main terminal on street level, 2nd floor to the *B*th floor being car parking floors. $(B+1)$th to $[(B+Y)$th $= N$th$]$ are occupant floors. This assumption applies to most modern office buildings without loss of generality.

PTPV is an N x 1 vector. **PTPV**(1) to **PTPV**(B) represent the probability of arrival of a passenger entering or leaving a particular floor within the entrance/exit floor stack, i.e. $P_{arr}(1)$, $P_{arr}(2)$, ..., $P_{arr}(B)$.

As stated before, more passengers enter and leave the building via the main terminal; hence **PTPV**(1) = $P_{arr}(1)$ is relatively larger, say 60% or more, while the remaining elements share the remaining 40% or less because sum **PTPV**(1) + ... + **PTPV**(B) must be equal to unity. **PTPV**(B+1) represents the relative population density of the lowest floor of the occupant floor stack, which is equal to $U(B+1)/U$ and **PTPV**(B+Y) represents the relative population density of the highest floor of the occupant floor stack, which is $U(B+Y)/U$, others similarly defined. Again, **PTPV**(B+1) + **PTPV**(B+2) + ... + **PTPV**(B+Y-1) + **PTPV**(B+Y) must be equal to unity.

The **PDFOD** = **PTPV** * **PTPV**^{T} is an N x N square matrix. Each element **PDFOD**(i , j) represents the probability a passenger wants to travel from the ith floor to the jth floor, i or j = 1, ..., N. It is reasonable nobody wants to travel from the ith floor to the ith floor and therefore all elements **PDFOD**(i , i) must be zero. Characteristics of **PDFOD** are shown in equation set (4) and all elements can be categorized under four zones or regions.

$$\sum_{i=1}^{B} P_{arr}(i) = 1 \quad ; \quad \sum_{i=1}^{Y} \frac{U(B+i)}{U} = 1 \text{ where } U = \sum_{i=1}^{Y} U(B+i)$$

$$\text{For } i \neq j, \quad \mathbf{PDFOD}(i,j) = \left\{ \begin{array}{lll} P_{arr}(i)P_{arr}(j) & (1 \le i \le B) \wedge (1 \le j \le B) & \text{inter-entrance floor traffic} \\ P_{arr}(i)\dfrac{U(j)}{U} & (1 \le i \le B) \wedge (B+1 \le j \le B+Y) & \text{incoming traffic} \\ \dfrac{U(i)}{U}P_{arr}(j) & (B+1 \le i \le B+Y) \wedge (1 \le j \le B) & \text{outgoing traffic} \\ \dfrac{U(i)U(j)}{U^2} & (B+1 \le i \le B+Y) \wedge (B+1 \le j \le B+Y) & \text{interfloor traffic} \end{array} \right\} \quad (4)$$

$$\mathbf{PDFOD}(i,i) = 0$$

Since passengers are rational, who do not travel from the ith floor to the ith floor, all **PDFOD**(i , i), i = 1, ..., N must be set to zero. Since $ie + ic + og + if = 1$ as discussed before, every element inside the **PDFOD** must be normalized in accordance with equation set (5). After this normalization process, the sum of all elements within the final **PDFOD** becomes unity.

$$\begin{array}{ll} \mathbf{PDFOD}(i,j) \leftarrow \dfrac{\mathbf{PDFOD}(i,j)\cdot ie}{\sum_{m=1}^{B}\sum_{n=1}^{B}\mathbf{PDFOD}(m,n)} & (1 \le i \le B) \wedge (1 \le j \le B) \quad \text{inter-entrance floors} \\ \mathbf{PDFOD}(i,j) \leftarrow \dfrac{\mathbf{PDFOD}(i,j)\cdot ic}{\sum_{m=1}^{B}\sum_{n=B+1}^{N}\mathbf{PDFOD}(m,n)} & (1 \le i \le B) \wedge (B+1 \le j \le N) \quad \text{incoming floors} \\ \mathbf{PDFOD}(i,j) \leftarrow \dfrac{\mathbf{PDFOD}(i,j)\cdot og}{\sum_{m=B+1}^{N}\sum_{n=1}^{B}\mathbf{PDFOD}(m,n)} & (B+1 \le i \le N) \wedge (1 \le j \le B) \quad \text{outgoing floors} \\ \mathbf{PDFOD}(i,j) \leftarrow \dfrac{\mathbf{PDFOD}(i,j)\cdot if}{\sum_{m=B+1}^{N}\sum_{n=B+1}^{N}\mathbf{PDFOD}(m,n)} & (B+1 \le i \le N) \wedge (B+1 \le j \le N) \quad \text{interfloor floors} \end{array} \quad (5)$$

This matrix, **PDFOD** is extremely important in the subsequent Monte Carlo simulation.

From **PDFOD**, **CDFOD** is generated according to equation (6). This **CDFOD** is also an N x N matrix.

$$\mathbf{CDFOD}(i,j)=\sum_{m=1}^{i-1}\sum_{n=1}^{N}\mathbf{PDFOD}(m,n)+\sum_{n=1}^{j}\mathbf{PDFOD}(i,n) \tag{6}$$

To produce a particular passenger within one round trip in the Monte Carlo simulation, a random number, $0 \le R \le 1$, is generated while the passenger's origin floor (i), and the destination floor (j) can be determined based on one of the two following criteria as shown in equation set (7). For the second criterion, $j = 1$.

$$\begin{aligned}&\mathbf{CDFOD}(i,j-1) < R \le \mathbf{CDFOD}(i,j) \quad \text{or}\\ &\mathbf{CDFOD}(i-1,N) < R \le \mathbf{CDFOD}(i,1) \quad \wedge \quad j=1\end{aligned} \tag{7}$$

It can be seen that **CDFOD**(1,1) = 0 while **CDFOD**(N , N) = 1 while all other elements are real numbers between 0 and 1, inclusive. To simulate one round trip, first of all, the total number of passengers, P, who demand service must be suggested. Since there is no more constraint, $P \le CC$, now, not all P passengers may be served within the same round trip though the demand is P; it really depends on the relative distribution of them. By using **CDFOD**, the origin and destination floors of all these P passengers are determined as P number of random number generations is performed.

For one particular round trip, the elevator car undergoes an up-journey, followed by a down-journey. The car always starts at the lowest floor with at least one up-going passenger, picks the passenger(s) up, stops at the highest floor to release the last up-going passenger, changes its direction, picks up the first down-going passenger at the highest floor with this passenger, and finally releases the last down-going passenger at this passenger's destination floor. It should be noted that the highest floor during the up-journey may not be the same as the highest floor during the down-journey while the lowest floor during the up-journey may not be the same as the lowest floor during the down-journey.

The number of stops during the up-journey and the down-journey is different and their sum gives the total number of stops. However, very often, the lowest stop of an up-journey is identical to that of a down-journey, and similarly for the highest stop. Whenever there is any overlapping of either the lowest floor and/or the highest floor, one or two stops must be subtracted from the total. The total time for a round trip is the RTT in this article. The round trip always starts from the lowest floor of the up-journey and ends on the same floor, as discussed before using the new definition of the ring concept of a round trip. By Monte Carlo simulation, half a million trials are conducted, and the average results are statistically used.

During a particular round trip, the exact total number of passengers that can be served is termed handling capacity, HC, in this article, which is equal to or less than the total demand of that round trip, P. This HC number of passengers can be divided into two groups, those up-going and those down-going and their sum is HC and $HC \le P$. After half a million trials, the average number of up-going passengers, PUP, and the average number of down-going passengers, PDN, can be estimated. At the lowest stop of the up-journey, certain passengers enter the car. At the next stop along the up-journey, some passengers may exit and enter the car. This process continues until the car is full. Then, the remaining passengers on the floor cannot be served anymore. A full car does not stop at any floor with waiting passengers only. The exact time spent by each passenger inside the car is recorded, called transit time, TT. There are up-transit and down-transit times respectively as it is assumed that no up-passenger stays inside a down-traveling car. Again, the average up-TT ($ATTUP$) and down-TT ($ATTDN$) of half a million trials are used. To calculate the overall mean transit time, MTT, of half a million trials, equation (8) is used. These are parameters used for analysis in the simulation.

$$MTT = \frac{PUP * ATTUP + PDN * ATTDN}{(PUP + PDN)} \quad (8)$$

As mentioned before, though *P* is fixed, the exact *HC* of each round trip differs because it very much depends on the distribution of these *P* passengers of that particular round trip. This is the core subject of consideration in this article. Table 1 shows an example with some exaggeration of course. For example, $N = 4$ is considered, $CC = 10$ and $P = 30$. The table provides a comparison between two rather extreme scenarios.

Table 1 Comparison of Extreme Scenarios that affect Handling Capacity significantly

Scenario 1			Scenario 2	
Number of passengers	From Floor/To Floor		Number of passengers	From Floor/To Floor
10	1/2		20	1/4
10	2/3		5	2/3
10	3/4		5	3/4
Total passengers handled = 30			Total passengers handled = 10	

In both cases, there are 30 passengers who demand service. In scenario 1, the elevator can handle all 30 passengers ($HC = 30$) within the same round trip, while in scenario 2, only 10 passengers ($HC = 10$) can be entertained. Even on the first floor, only half of the 20 waiting passengers can get into the elevator which bypasses both 2nd and 3rd floors. Obviously, the *RTT* of scenario 1 is certainly much longer than that of scenario 2. Which one is more favorable very much depends on the average waiting time, *AWT*, and the average transit time, *ATT*, of passengers. In traditional traffic analysis by calculation, these scenarios are not considered because only incoming traffic during an uppeak period is considered, and therefore the overall design tends to be too ideal and over-simplified, and from time to time, the system is over-sized. In this study, the consideration is more realistic and a more practical *RTT* is arrived at by simulation.

3 THE MONTE CARLO SIMULATION

The study is on a building with the main terminal at the ground floor (1st floor), two parking floors above (2/F and 3/F), and then eight occupant floors (4/F to 11/F), i.e. $N = 11$. Floor height is assumed uniform with the following technical parameters of the elevator as shown in Table 2.

Table 2 Technical Parameters of the Elevator under study

Parameter	Value	Parameter	Value
CC	10 passengers	t_v	2 s
d_f	4 m	v	2 m/s
t_o	1 s	t_c	3 s
$t_f(1)$	4.7 s	t_p	1.2 s
t_{pre}	0 s	t_{sd}	0 s
B	3 floors	Y	8 floors
N	11 floors		

Table 3 shows the **PTPV** of this building. Most passengers enter and exit the building via the first floor. The population of all occupant floors is uniform. Different ratios of *ie*: *ic*: *og*: *if* have been used and the results are discussed in the next section. Table 4(a) shows the final **PDFOD** matrix and Table 4(b) the **CDFOD** matrix.

Table 3 Passenger Transition Probability Vector for simulation (uniform population distribution on occupant floors)

$P_{arr}(1)$	$P_{arr}(2)$	$P_{arr}(3)$	$U(4)/U$	$U(5)/U$	$U(6)/U$
0.6	0.2	0.2	0.125	0.125	0.125
$U(7)/U$	$U(8)/U$	$U(9)/U$	$U(10)/U$	$U(11)/U$	
0.125	0.125	0.125	0.125	0.125	

Table 4(a) The Probability Distribution Function Origin-Destination Matrix after normalization (uniform population distribution)

0.0000	0.0000	0.0000	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262
0.0000	0.0000	0.0000	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087
0.0000	0.0000	0.0000	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087	0.0087
0.0262	0.0087	0.0087	0.0000	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054
0.0262	0.0087	0.0087	0.0054	0.0000	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054
0.0262	0.0087	0.0087	0.0054	0.0054	0.0000	0.0054	0.0054	0.0054	0.0054	0.0054
0.0262	0.0087	0.0087	0.0054	0.0054	0.0054	0.0000	0.0054	0.0054	0.0054	0.0054
0.0262	0.0087	0.0087	0.0054	0.0054	0.0054	0.0054	0.0000	0.0054	0.0054	0.0054
0.0262	0.0087	0.0087	0.0054	0.0054	0.0054	0.0054	0.0054	0.0000	0.0054	0.0054
0.0262	0.0087	0.0087	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054	0.0000	0.0054
0.0262	0.0087	0.0087	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054	0.0000

Table 4(b) The Cumulative Distribution Frequency Origin-Destination Matrix (uniform population distribution)

0.0000	0.0000	0.0000	0.0262	0.0525	0.0787	0.1050	0.1312	0.1575	0.1837	0.2100
0.2100	0.2100	0.2100	0.2187	0.2275	0.2362	0.2450	0.2537	0.2625	0.2712	0.2800
0.2800	0.2800	0.2800	0.2887	0.2975	0.3062	0.3150	0.3237	0.3325	0.3412	0.3500
0.3762	0.3850	0.3937	0.3937	0.3991	0.4045	0.4098	0.4152	0.4205	0.4259	0.4312
0.4575	0.4662	0.4750	0.4804	0.4804	0.4857	0.4911	0.4964	0.5018	0.5071	0.5125
0.5387	0.5475	0.5562	0.5616	0.5670	0.5670	0.5723	0.5777	0.5830	0.5884	0.5937
0.6200	0.6287	0.6375	0.6429	0.6482	0.6536	0.6536	0.6589	0.6643	0.6696	0.6750
0.7012	0.7100	0.7187	0.7241	0.7295	0.7348	0.7402	0.7402	0.7455	0.7509	0.7562
0.7825	0.7912	0.8000	0.8054	0.8107	0.8161	0.8214	0.8268	0.8268	0.8321	0.8375
0.8637	0.8725	0.8812	0.8866	0.8920	0.8973	0.9027	0.9080	0.9134	0.9134	0.9187
0.9450	0.9537	0.9625	0.9679	0.9732	0.9786	0.9839	0.9893	0.9946	1.0000	1.0000

Altogether, twelve scenarios have been studied by Monte Carlo simulation. The first four belong to the typical or normal office traffic patterns including uppeak, down peak, and two lunch peaks based on Chapter 4 of CIBSE (2020). By these four scenarios, the general performance of several selected parameters under these regular traffic patterns could be studied. Then, eight more scenarios which behave in between those typical patterns or under extreme conditions have been studied to find out the trends in more detail. Since it is assumed that all P passengers have already been waiting on different floors at the beginning of each round trip simulation, it is difficult to study their overall waiting time. Therefore, AWT is not included in the simulation process discussed by this article.

The building, entrance/exit - occupant floor arrangement, all elevator static/dynamic parameters, and the population distribution on each floor remain unchanged throughout the simulation process because the target is to understand the changes in selected parameters upon the variation of P of each round trip. All passenger flows between inter-entrance/exit floors are ignored because the chance of occurrence is low enough to be neglected. These twelve scenarios are shown in Table 5.

Table 5 Details of the 12 scenarios under simulation

Scenario	Type	$P_{arr}(1)$	$P_{arr}(2)$	$P_{arr}(3)$	ic	og	if
1	Uppeak	0.6	0.2	0.2	0.85	0.10	0.05
2	Down peak	0.6	0.2	0.2	0.10	0.85	0.05
3	Lunch 1	0.6	0.2	0.2	0.45	0.45	0.10
4	Lunch 2	0.6	0.2	0.2	0.40	0.40	0.20
5	Weak Uppeak with Interfloor	0.6	0.2	0.2	0.55	0.15	0.30
6	Weak Down peak with Interfloor	0.6	0.2	0.2	0.15	0.55	0.30
7	Uppeak with Interfloor	0.6	0.2	0.2	0.70	0.00	0.30
8	Down peak with Interfloor	0.6	0.2	0.2	0.00	0.70	0.30
9	Mixed	0.6	0.2	0.2	0.35	0.35	0.30
10	Pure Incoming	0.6	0.2	0.2	1.00	0.00	0.00
11	Pure Outgoing	0.6	0.2	0.2	0.00	1.00	0.00
12	Pure Interfloor	0.6	0.2	0.2	0.00	0.00	1.00

The raw results after 500,000 trials of random passenger generation and simulation are shown in the following tables. Those (a)'s are raw data while (b)'s are processed data.

Table 6(a) *ie* = 0.00; *ic* = 0.85; *og* = 0.10; *if* = 0.05 Uppeak Scenario 1

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	8.262	8.564	8.009	7.496	7.201	7.270
# of down-stops	2.211	2.576	3.273	3.896	5.220	6.272
Highest floor reached	10.700	10.762	10.795	10.816	10.861	10.896
Lowest floor reached	1.000	1.000	1.000	1.000	1.000	1.000
# of up-passengers	8.7	9.9	10.4	10.5	10.7	10.9
# of down-passengers	1.3	1.5	2.0	2.5	3.8	5.0
% of up-coincidental floors	0.156	0.187	0.240	0.287	0.386	0.466
% of down-coincidental floors	0.460	0.524	0.629	0.711	0.844	0.916
Round trip time (s)	128.837	136.281	138.619	139.999	149.043	159.192
Average up-transit time (s)	52.294	54.951	53.492	51.244	49.467	49.411
Average down-transit time (s)	17.232	19.353	23.059	26.086	32.149	36.968

Table 6(b) *ie* = 0.00; *ic* = 0.85; *og* = 0.10; *if* = 0.05 Uppeak Scenario 1

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	128.837	0.000	10.000	0.000	47.736	0.000	0.078
12	136.281	5.778	11.400	14.000	50.267	5.302	0.084
16	138.619	7.593	12.400	24.000	48.583	1.775	0.089
20	139.999	8.664	13.000	30.000	46.406	-2.786	0.093
30	149.043	15.683	14.500	45.000	44.928	-5.881	0.097
40	159.192	23.561	15.900	59.000	45.498	-4.688	0.100

Table 7(a) *ie* = 0.00; *ic* = 0.10; *og* = 0.85; *if* = 0:05 Down Peak Scenario 2

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	2.209	2.577	3.270	3.896	5.216	6.272
# of down-stops	8.263	8.582	8.098	7.507	6.486	5.876
Highest floor reached	10.698	10.786	10.886	10.937	10.986	10.996
Lowest floor reached	1.000	1.000	1.000	1.000	1.000	1.000
# of up-passengers	1.3	1.5	2.0	2.5	3.7	5.0
# of down-passengers	8.7	9.9	10.3	10.4	10.5	10.5
% of up-coincidental floors	0.157	0.187	0.247	0.303	0.427	0.528
% of down-coincidental floors	0.461	0.523	0.629	0.710	0.844	0.916
Round trip time (s)	128.810	136.514	139.488	140.349	143.966	148.916
Average up-transit time (s)	17.236	19.370	23.039	26.070	32.124	36.967
Average down-transit time (s)	52.295	55.338	56.039	55.430	53.916	52.861

Table 7(b) *ie* = 0.00; *ic* = 0.10; *og* = 0.85; *if* = 0:05 Down Peak Scenario 2

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	128.810	0.000	10.000	0.000	47.737	0.000	0.078
12	136.514	5.981	11.400	14.000	50.605	6.008	0.084
16	139.488	8.290	12.300	23.000	50.673	6.150	0.088
20	140.349	8.958	12.900	29.000	49.740	4.195	0.092
30	143.966	11.766	14.200	42.000	48.238	1.048	0.099
40	148.916	15.609	15.500	55.000	47.734	-0.007	0.104

Table 8(a) *ie* = 0.00; *ic* = 0.45; *og* = 0.45; *if* = 0:10 Lunch 1 Scenario 3

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	6.253	6.930	7.950	8.520	8.401	7.918
# of down-stops	6.251	6.929	7.960	8.545	8.505	7.898
Highest floor reached	10.723	10.806	10.898	10.941	10.979	10.991
Lowest floor reached	1.000	1.000	1.000	1.000	1.000	1.000
# of up-passengers	5.0	6.0	7.9	9.5	11.2	11.7
# of down-passengers	5.0	6.0	7.9	9.5	11.2	11.5
% of up-coincidental floors	0.332	0.394	0.506	0.599	0.732	0.795
% of down-coincidental floors	0.915	0.954	0.987	0.996	1.000	1.000
Round trip time (s)	138.317	151.839	174.228	188.994	195.315	189.682
Average up-transit time (s)	38.882	42.395	48.173	51.986	53.081	50.959
Average down-transit time (s)	38.873	42.392	48.277	52.425	56.054	56.065

Table 8(b) ***ie*** **= 0.00;** ***ic*** **= 0.45;** ***og*** **= 0.45;** ***if*** **= 0:10 Lunch 1 Scenario 3**

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	138.317	0.000	10.000	0.000	38.878	0.000	0.072
12	151.839	9.776	12.000	20.000	42.394	9.044	0.079
16	174.228	25.963	15.800	58.000	48.225	24.043	0.091
20	188.994	36.638	19.000	90.000	52.206	34.282	0.101
30	195.315	41.208	22.400	124.000	54.568	40.358	0.115
40	189.682	37.136	23.200	132.000	53.490	37.586	0.122

Table 9(a) ***ie*** **= 0.00;** ***ic*** **= 0.40;** ***og*** **= 0.40;** ***if*** **= 0:20 Lunch 2 Scenario 4**

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	6.400	7.093	8.146	8.804	8.995	8.518
# of down-stops	6.400	7.087	8.146	8.826	9.146	8.724
Highest floor reached	10.768	10.840	10.922	10.958	10.988	10.996
Lowest floor reached	1.001	1.000	1.000	1.000	1.000	1.000
# of up-passengers	5.0	6.0	8.0	9.7	12.3	13.2
# of down-passengers	5.0	6.0	8.0	9.7	12.2	13.0
% of up-coincidental floors	0.359	0.424	0.544	0.643	0.791	0.859
% of down-coincidental floors	0.873	0.926	0.975	0.992	0.999	1.000
Round trip time (s)	140.573	154.116	176.902	193.701	208.296	205.991
Average up-transit time (s)	37.389	40.715	46.283	50.301	53.121	51.434
Average down-transit time (s)	37.395	40.684	46.298	50.565	55.576	56.420

Table 9(b) ***ie*** **= 0.00;** ***ic*** **= 0.40;** ***og*** **= 0.40;** ***if*** **= 0:20 Lunch 2 Scenario 4**

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	140.573	0.000	10.000	0.000	37.392	0.000	0.071
12	154.116	9.634	12.000	20.000	40.700	8.845	0.078
16	176.902	25.844	16.000	60.000	46.291	23.798	0.090
20	193.701	37.794	19.400	94.000	50.433	34.876	0.100
30	208.296	48.176	24.500	145.000	54.343	45.335	0.118
40	205.991	46.537	26.200	162.000	53.908	44.170	0.127

Table 10(a) ***ie*** **= 0.00;** ***ic*** **= 0.55;** ***og*** **= 0.15;** ***if*** **= 0:30 Weak Uppeak with Interfloor Scenario 5**

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	7.717	8.397	9.154	9.190	8.488	8.188
# of down-stops	4.782	5.373	6.403	7.252	8.714	9.516
Highest floor reached	10.806	10.869	10.933	10.960	10.984	10.994
Lowest floor reached	1.005	1.001	1.000	1.000	1.000	1.000
# of up-passengers	6.9	8.3	10.8	12.2	13.6	14.6
# of down-passengers	3.1	3.7	4.8	6.0	9.0	11.7
% of up-coincidental floors	0.357	0.420	0.530	0.618	0.758	0.844
% of down-coincidental floors	0.616	0.681	0.779	0.849	0.940	0.977
Round trip time (s)	140.436	153.137	172.610	183.852	197.997	203.394

Average up-transit time (s)	43.407	47.116	52.148	53.469	51.063	49.451
Average down-transit time (s)	26.702	28.671	32.334	35.575	41.995	46.560

Table 10(b) *ie* = 0.00; *ic* = 0.55; *og* = 0.15; *if* = 0:30 Weak Uppeak with Interfloor Scenario 5

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	140.436	0.000	10.000	0.000	38.228	0.000	0.071
12	153.137	9.044	12.000	20.000	41.429	8.372	0.078
16	172.610	22.910	15.600	56.000	46.051	20.464	0.090
20	183.852	30.915	18.200	82.000	47.570	24.436	0.099
30	197.997	40.987	22.600	126.000	47.452	24.127	0.114
40	203.394	44.830	26.300	163.000	48.165	25.992	0.129

Table 11(a) *ie* = 0.00; *ic* = 0.15; *og* = 0.55; *if* = 0:30 Weak Down peak with Interfloor Scenario 6

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	4.785	5.370	6.401	7.255	8.722	8.518
# of down-stops	7.719	8.401	9.192	9.313	8.727	8.232
Highest floor reached	10.806	10.870	10.939	10.970	10.995	10.999
Lowest floor reached	1.004	1.001	1.000	1.000	1.000	1.000
# of up-passengers	3.1	3.7	4.8	6.0	9.0	11.7
# of down-passengers	6.9	8.3	10.8	12.2	13.3	13.7
% of up-coincidental floors	0.358	0.418	0.532	0.627	0.799	0.889
% of down-coincidental floors	0.617	0.681	0.779	0.850	0.942	0.977
Round trip time (s)	140.458	153.152	172.856	184.618	198.644	207.307
Average up-transit time (s)	26.742	28.681	32.303	35.584	42.009	46.539
Average down-transit time (s)	43.405	47.129	52.555	55.204	56.435	56.302

Table 11(b) *ie* = 0.00; *ic* = 0.15; *og* = 0.55; *if* = 0:30 Weak Down peak with Interfloor Scenario 6

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	140.458	0.000	10.000	0.000	38.239	0.000	0.071
12	153.152	9.038	12.000	20.000	41.441	8.372	0.078
16	172.856	23.066	15.600	56.000	46.324	21.141	0.090
20	184.618	31.440	18.200	82.000	48.736	27.449	0.099
30	198.644	41.426	22.300	123.000	50.613	32.358	0.112
40	207.307	47.594	25.400	154.000	51.805	35.475	0.123

Table 12(a) *ie* = 0.00; *ic* = 0.70; *og* = 0.00; *if* = 0:30 Uppeak with Interfloor Scenario 7

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	8.298	8.940	9.110	8.663	8.092	8.093
# of down-stops	3.167	3.434	3.955	4.447	5.497	6.273
Highest floor reached	10.817	10.875	10.920	10.940	10.971	10.986
Lowest floor reached	1.005	1.002	1.000	1.000	1.000	1.000
# of up-passengers	8.1	9.8	11.8	12.5	13.6	14.6
# of down-passengers	1.9	2.1	2.6	3.1	4.5	6.0
% of up-coincidental floors	0.340	0.382	0.453	0.511	0.641	0.739
% of down-coincidental floors	0.000	0.000	0.000	0.000	0.000	0.000
Round trip time (s)	137.793	148.517	158.782	161.686	170.174	180.628
Average up-transit time (s)	47.556	51.611	54.088	52.611	49.747	49.110
Average down-transit time (s)	18.414	19.191	20.772	22.295	25.754	28.717

Table 12(b) *ie* = 0.00; *ic* = 0.70; *og* = 0.00; *if* = 0:30 Uppeak with Interfloor Scenario 7

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	137.793	0.000	10.000	0.000	42.019	0.000	0.073
12	148.517	7.783	11.900	19.000	45.890	9.212	0.080
16	158.782	15.232	14.400	44.000	48.073	14.407	0.091
20	161.686	17.340	15.600	56.000	46.587	10.870	0.096
30	170.174	23.500	18.100	81.000	43.782	4.195	0.106
40	180.628	31.086	20.600	106.000	43.170	2.740	0.114

Table 13(a) *ie* = 0.00; *ic* = 0.00; *og* = 0.70; *if* = 0:30 Down peak with Interfloor Scenario 8

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	3.161	3.427	3.952	4.448	5.497	6.270
# of down-stops	8.306	8.948	9.216	8.869	8.067	7.597
Highest floor reached	10.816	10.876	10.940	10.971	10.995	10.999
Lowest floor reached	1.005	1.002	1.000	1.000	1.000	1.000
# of up-passengers	1.9	2.1	2.6	3.1	4.5	6.0
# of down-passengers	8.1	9.8	11.8	12.4	12.9	13.2
% of up-coincidental floors	0.338	0.380	0.457	0.529	0.675	0.780
% of down-coincidental floors	0.000	0.000	0.000	0.000	0.000	0.000
Round trip time (s)	137.807	148.533	159.513	162.841	168.276	173.679
Average up-transit time (s)	18.398	19.180	20.765	22.300	25.784	28.719
Average down-transit time (s)	47.596	51.636	55.639	56.471	56.301	55.949

Table 13(b) *ie* = 0.00; *ic* = 0.00; *og* = 0.70; *if* = 0:30 Down peak with Interfloor Scenario 8

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	137.807	0.000	10.000	0.000	42.048	0.000	0.073
12	148.533	7.783	11.900	19.000	45.908	9.180	0.080
16	159.513	15.751	14.400	44.000	49.342	17.347	0.090
20	162.841	18.166	15.500	55.000	49.637	18.047	0.095
30	168.276	22.110	17.400	74.000	48.409	15.126	0.103
40	173.679	26.031	19.200	92.000	47.440	12.822	0.111

Table 14(a) ***ie*** **= 0.00;** ***ic*** **= 0.35;** ***og*** **= 0.35;** ***if*** **= 0:30 Mixed Scenario 9**

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	6.507	7.208	8.282	8.989	9.442	9.012
# of down-stops	6.510	7.213	8.282	9.003	9.579	9.335
Highest floor reached	10.805	10.870	10.939	10.970	10.993	10.998
Lowest floor reached	1.005	1.001	1.000	1.000	1.000	1.000
# of up-passengers	5.0	6.0	8.0	9.9	13.1	14.5
# of down-passengers	5.0	6.0	8.0	9.9	13.1	14.3
% of up-coincidental floors	0.386	0.456	0.581	0.682	0.835	0.901
% of down-coincidental floors	0.817	0.884	0.954	0.982	0.998	1.000
Round trip time (s)	142.353	155.910	178.777	196.605	217.893	219.359
Average up-transit time (s)	35.906	39.012	44.276	48.317	52.609	51.766
Average down-transit time (s)	35.894	39.033	44.275	48.446	54.179	55.692

Table 14(b) ***ie*** **= 0.00;** ***ic*** **= 0.35;** ***og*** **= 0.35;** ***if*** **= 0:30 Mixed Scenario 9**

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	142.353	0.000	10.000	0.000	35.900	0.000	0.070
12	155.910	9.524	12.000	20.000	39.023	8.698	0.077
16	178.777	25.587	16.000	60.000	44.276	23.330	0.089
20	196.605	38.111	19.800	98.000	48.382	34.767	0.101
30	217.893	53.065	26.200	162.000	53.394	48.730	0.120
40	219.359	54.095	28.800	188.000	53.715	49.625	0.131

Table 15(a) ***ie*** **= 0.00;** ***ic*** **= 1.00;** ***og*** **= 0.00;** ***if*** **= 0:00 Pure Incoming Scenario 10**

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	8.680	8.208	7.391	7.024	6.896	6.895
# of down-stops	0.000	0.000	0.000	0.000	0.000	0.000
Highest floor reached	10.670	10.670	10.669	10.671	10.668	10.670
Lowest floor reached	1.000	1.000	1.000	1.000	1.000	1.000
# of up-passengers	10.0	10.0	10.0	10.0	10.0	10.0
# of down-passengers	0.0	0.0	0.0	0.0	0.0	0.0
% of up-coincidental floors	0.000	0.000	0.000	0.000	0.000	0.000
% of down-coincidental floors	0.000	0.000	0.000	0.000	0.000	0.000
Round trip time (s)	120.836	117.674	112.201	109.748	108.877	108.877
Average up-transit time (s)	56.217	55.060	51.759	49.974	49.301	49.291
Average down-transit time (s)	0.000	0.000	0.000	0.000	0.000	0.000

Table 15(b) ***ie*** **= 0.00;** ***ic*** **= 1.00;** ***og*** **= 0.00;** ***if*** **= 0:00 Pure Incoming Scenario 10**

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	120.836	0.000	10.000	0.000	56.217	0.000	0.083
12	117.674	-2.617	10.000	0.000	55.060	-2.058	0.085
16	112.201	-7.146	10.000	0.000	51.759	-7.930	0.089
20	109.748	-9.176	10.000	0.000	49.974	-11.105	0.091

30	108.877	-9.897	10.000	0.000	49.301	-12.302	0.092
40	108.977	-9.814	10.000	0.000	49.291	-12.320	0.092

Table 16(a) *ie* = 0.00; *ic* = 0.00; *og* = 1.00; *if* = 0:00 Pure Outgoing Scenario 11

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	0.000	0.000	0.000	0.000	0.000	0.000
# of down-stops	8.681	8.258	7.446	6.828	5.816	5.223
Highest floor reached	10.670	10.763	10.871	10.927	10.981	10.995
Lowest floor reached	1.000	1.000	1.000	1.000	1.000	1.000
# of up-passengers	0.0	0.0	0.0	0.0	0.0	0.0
# of down-passengers	10.0	10.0	10.0	10.0	10.0	10.0
% of up-coincidental floors	0.000	0.000	0.000	0.000	0.000	0.000
% of down-coincidental floors	0.000	0.000	0.000	0.000	0.000	0.000
Round trip time (s)	120.842	118.377	113.370	109.456	102.894	98.976
Average up-transit time (s)	0.000	0.000	0.000	0.000	0.000	0.000
Average down-transit time (s)	56.221	56.260	55.231	54.250	52.370	51.158

Table 16(b) *ie* = 0.00; *ic* = 0.00; *og* = 1.00; *if* = 0:00 Pure Outgoing Scenario 11

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	120.842	0.000	10.000	0.000	56.221	0.000	0.083
12	118.377	-2.040	10.000	0.000	56.200	-0.037	0.084
16	113.370	-6.183	10.000	0.000	55.231	-1.761	0.088
20	109.456	-9.422	10.000	0.000	54.250	-3.506	0.091
30	102.894	-14.852	10.000	0.000	52.370	-6.850	0.097
40	98.976	-18.095	10.000	0.000	51.158	-9.006	0.101

Table 17(a) *ie* = 0.00; *ic* = 0.00; *og* = 0.00; *if* = 1.00 Pure Interfloor Scenario 12

# of passengers demanding service around the building	10 (*CC*)	12 (1.2 *CC*)	16 (1.6 *CC*)	20 (2 *CC*)	30 (3 *CC*)	40 (4 *CC*)
# of up-stops	5.894	6.388	7.057	7.443	7.793	7.787
# of down-stops	5.896	6.387	7.035	7.443	7.792	7.787
Highest floor reached	10.941	10.967	10.982	10.997	11.000	11.000
Lowest floor reached	4.058	4.032	4.010	4.003	4.000	4.000
# of up-passengers	5.0	6.0	8.0	10.0	14.3	16.9
# of down-passengers	5.0	6.0	8.0	10.0	14.3	16.9
% of up-coincidental floors	0.566	0.652	0.782	0.866	0.962	0.987
% of down-coincidental floors	0.566	0.651	0.782	0.869	0.962	0.987
Round trip time (s)	122.934	133.403	150.383	163.949	187.941	200.277
Average up-transit time (s)	27.049	28.979	32.097	34.556	38.858	40.910
Average down-transit time (s)	27.058	28.966	32.083	34.571	38.861	40.900

Table 17(b) *ie* = 0.00; *ic* = 0.00; *og* = 0.00; *if* = 1.00 Pure Interfloor Scenario 12

P	*RTT*	% increase	*HC*	% increase	*MTT* (up-down ave)	% increase	*HC*/*RTT*
10	122.934	0.000	10.000	0.000	27.054	0.000	0.081
12	133.403	8.516	12.000	20.000	28.973	7.093	0.090

16	150.383	22.328	16.000	60.000	32.090	18.617	0.106
20	163.949	33.363	20.000	100.000	34.564	27.760	0.122
30	187.941	52.880	28.600	186.000	38.860	43.639	0.152
40	200.277	62.914	33.800	238.000	40.905	51.200	0.169

4 OBSERVATIONS AND ANALYSIS

Observations on Raw Data

It can be seen from most tables (a), e.g. Tables 11(a) and 17(a) etc., that the number of up-stops and number of down-stops keep on increasing as P is increasing in general, with three exceptions. Such an increase is reasonable because the main idea of this and the previous article (So et al. 2022b) states that a passenger demand of $P \leq CC$ in fact has not fully utilized the design capacity of the system. Such conclusion can also be arrived later when HC and HC/RTT are analyzed.

For those pure incoming (Table 15(a)) or pure outgoing (Table 16(a)), either one can always be zero because either type of traffic actually does not exist. Also, for these extreme cases, the number of up- or down-stops starts to decrease right from the beginning when P begins to go beyond CC. This is because the chance of more passengers who want to go to the same destination floor increases.

In general, the number of up- and/or down-stops start(s) to decrease as P approaches 4 CC. This is reasonable as the demand far exceeds the design capacity while the system has been driven to saturation.

For normal uppeak (Table 6(a)) and normal down peak (Table 7(a)) conditions, it can be seen that the number of stops of opposite direction of travel, i.e. down-stops under uppeak and vice versa, keeps on increasing even until $P = 4\ CC$. This is because one round trip must be considered as two separate journeys, i.e. the up-journey and the down-journey. The reason why the number of down-stops can continue to increase under an uppeak condition, and vice versa, is that the design capacity actually has not been fully utilized in the opposite direction.

Next, the highest and lowest floors reached are considered. Except pure interfloor (Table 17(a)), for all scenarios, the highest floor reached gradually approaches the top floor, i.e. 11th floor, and the lowest floor reached gradually approaches the bottom floor, i.e. 1st floor, as P is increasing. Even under a pure interfloor condition, the highest floor reached approaches the top floor while the lowest floor reached approaches the 4th floor which is the bottom floor of the occupant floor zone. This is obvious because as P is getting larger, the chance of origin and destination floors taking all floors of the whole building is getting higher and higher.

Finally, the proportion, indicated by symbol % between 0.0 and 1.0, of up-coincidental floors and down-coincidental floors is considered. As P is getting larger, it can be seen that the proportion is approaching unity. The exact definition of the proportion of up-coincidental floors here means the percentage (between 0.0 and 1.0) of trials out of 500,000 where the first stop of an up-journey coincides with the last stop of a down-journey and this equally applies to the number of down-coincidental floors. As the demand, P, is increasing, more and more passengers enter the building at the 1st floor and exit there, as well as traveling to the top floor and entering the elevator at the top floor. Furthermore, the chance of up-coincidental floors is usually higher than that of down-coincidental floors, which is reasonable as the main terminal is supposed to be the busiest floor throughout the whole building.

Observations on Processed Data

Here, three important processed parameters are analyzed.

The *RTT* has a huge impact on system design. Throughout the decades, designers have been desiring to shorten the *RTT* of the round trip because *RTT* relates to the interval which is also related to the *AWT* of passengers. Therefore, *RTT* is the true indicator of the quality of service.

Second, the *HC* is important because this relates to the exact number of passengers that can be handled, which is related to the quantity of service. Readers are reminded that the definition of *HC* in this article is different from the conventional one which is the number of passengers that can be handled in a 5-minute interval. Here, the *HC* means the number of passengers that can be handled by one elevator within one round trip. In other words, a slightly longer *RTT* is worth considering provided that the *HC* is increasing by a certain level. Hence, the ratio *HC*/*RTT* is important, the higher the better, meaning that more output can be obtained with less input. This is somehow analogue to the concept of COP (coefficient of performance) in the HVAC (heating, ventilating and air-conditioning) industry. Even if more electrical energy is consumed by a chiller, it is worth it if the amount of heat removed by the chiller is also increased by a greater amount.

Finally, the *MTT* (mean transit time) is important as it indicates the average time when a passenger needs to spend inside an elevator on his/her way to the destination. In some way, the *MTT* together with the *AWT* represent the quality of service.

Figure 1 shows the variation of *RTT* against *P* under all 12 scenarios. It can be seen that in general, the *RTT* curve rises initially until it approaches $P = 4\ CC$. There are exceptions here. As explained in the last section, for CIBSE Office uppeak or CIBSE Office down peak conditions, the number of stops can continue to increase in either travel direction opposite to that of the peak condition. Under this situation, there is room for further increase in the *RTT* because not the full design capacity of the opposite travel direction has been utilized even when $P = 4\ CC$. Such performance can also be seen during a weak uppeak or weak down peak condition.

Figure 2 shows the variation of *HC* against *P* under all 12 scenarios. It can be seen that under all conditions, the *HC* keeps on increasing as *P* is increasing except the pure incoming, i.e. uppeak, and pure outgoing, i.e. down peak, conditions because the *HC* keeps constant as explained earlier. In other words, in general, the system always has some room for taking up more passengers when $P > CC$. In particular, during the two lunch peaks, mixed and pure interfloor conditions, *HC* can catch up with *P* up to $P = 2\ CC$. This is very encouraging. The system can handle more passengers when a more balanced up- and down- traffic conditions exist.

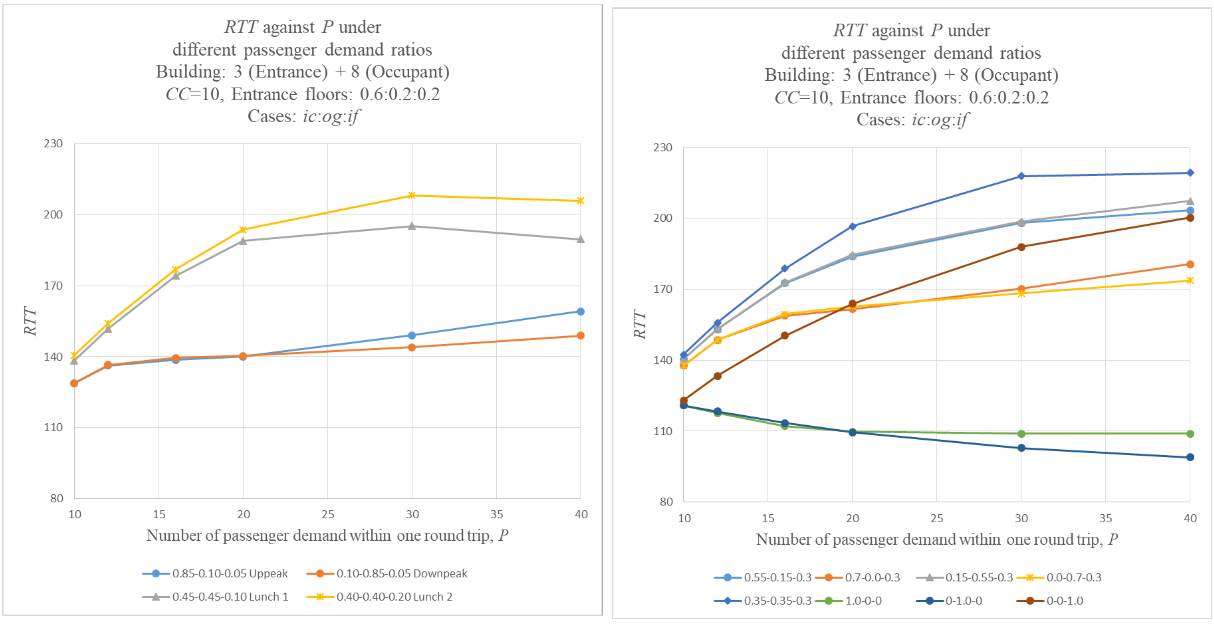

Figure 1 Round Trip Time against Passenger Demand under 12 scenarios

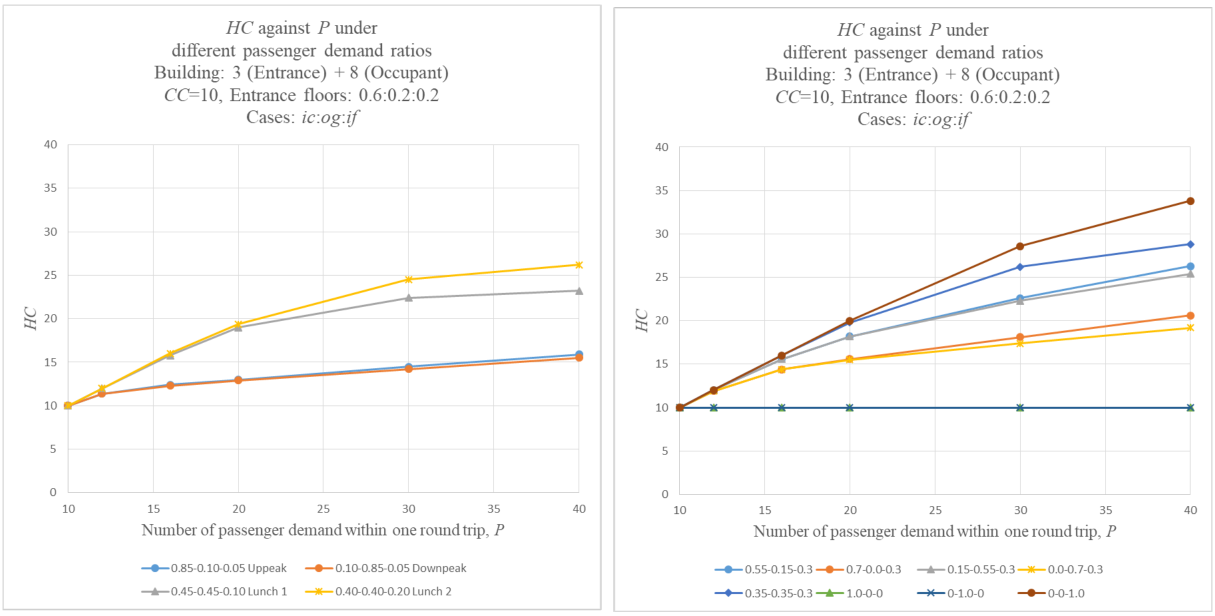

Figure 2 Handling Capacity against Passenger Demand under 12 scenarios

Whether a higher *HC* is really desirable or not very much depends on the cost of it, i.e. the *RTT*. Figure 3 shows the variation of *HC*/*RTT* against *P*. It can be seen that for most scenarios, except the pure incoming, i.e. uppeak, scenario, the curve is rising as *P* is increasing. That is desirable as the output, i.e. *HC*, is improving whereas the input, *RTT*, is not increasing by the same amount. The parameter, *HC*/*RTT* should be as high as possible. It seems that it is rather easy for a system to be saturated under a pure uppeak condition. That may explain why over the past decades, designers have been focusing on uppeak conditions only. First, it is mathematically easier to work on uppeak traffic. Second, it may be the worst case to consider. More discussion can be found in Chapter 13 of (Barney et. al. 2016). If the system is well designed to handle uppeak, it could be able to handle other traffic conditions more satisfactorily. Having said that, the ratio, *HC/RTT* still rises when *P* does not go beyond *CC* by too much, i.e. $P \leq 2\ CC$. With a view to the recent belief of the industry that pure incoming or uppeak is rare, the conventional design rules may oversize the system.

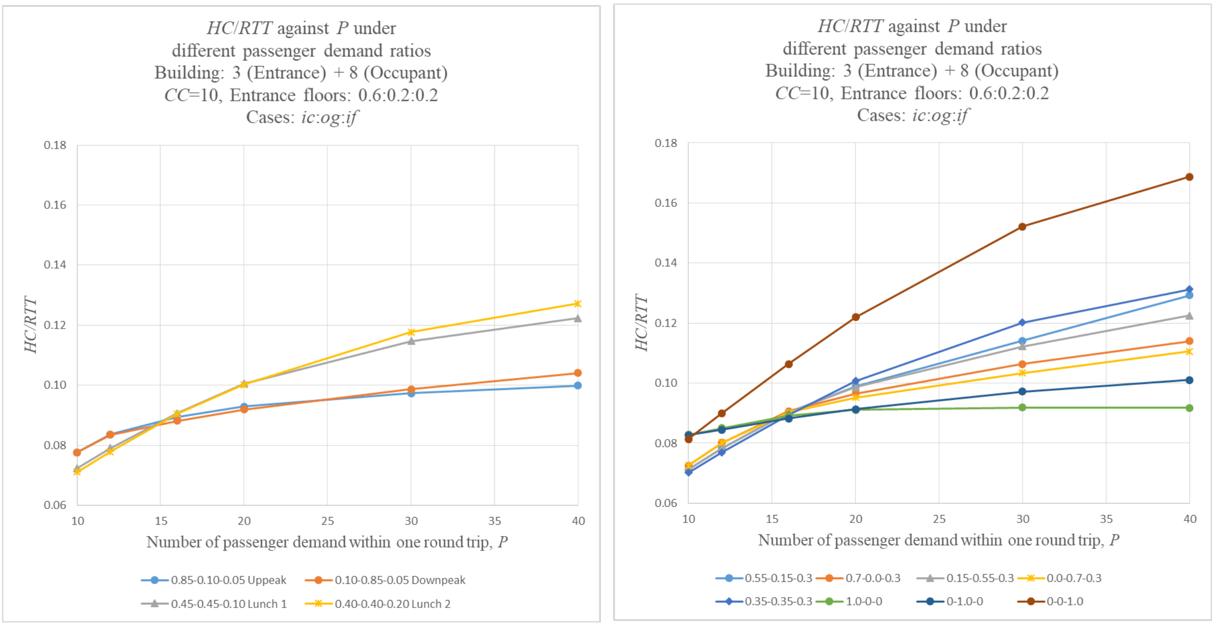

Figure 3 The ratio of *HC* over *RTT* against Passenger Demand under 12 scenarios

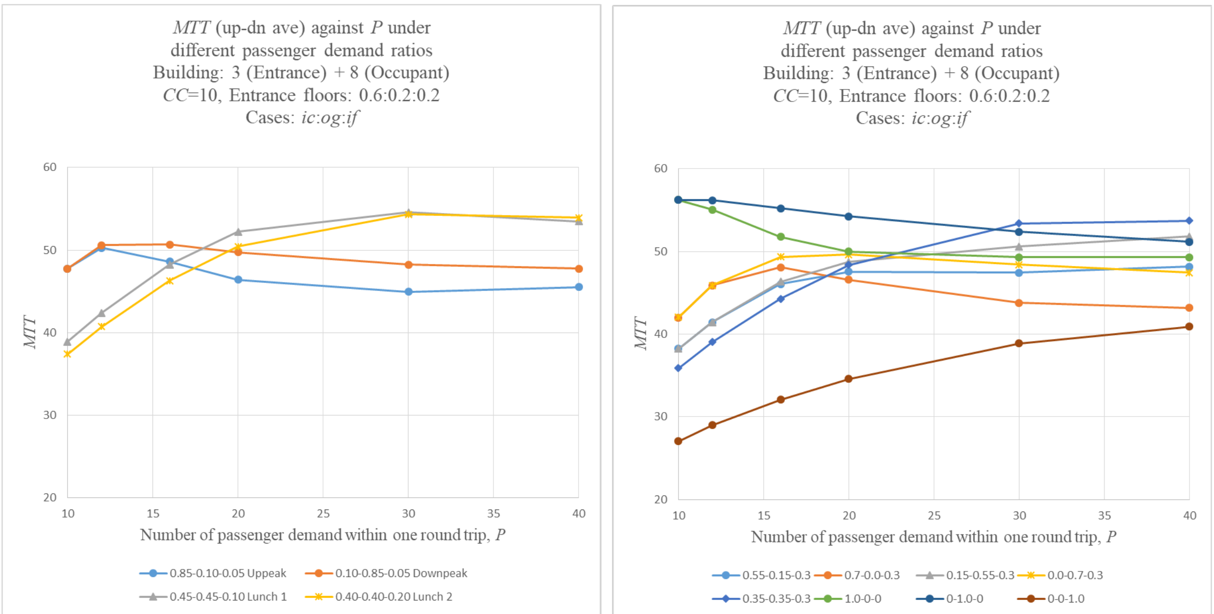

Figure 4 Mean Transit Time against Passenger Demand under 12 scenarios

The champion goes to Scenario 12, pure interfloor traffic, where the ratio is highest even when $P = 4\ CC$. First, the travel distance of the elevator is shorter during pure interfloor because the lift basically serves the occupant floor zone only, not the entire building. Second, there is a more or less balanced up- and down- traffic during such pure interfloor condition. However, the risk is that pure interfloor may consist of sub-uppeak or sub-down-peak conditions. Under such sub-conditions, the ratio may not be that high and the two curves of the two lunch peaks, i.e. Scenarios 3 and 4, should be referred to.

Finally, the second parameter indicating the quality of service other than the *AWT* is considered. Figure 4 shows the variation of *MTT* against *P*. It can be seen from the left chart that the curves of the two lunch peaks keep on rising until saturation, which is not a desirable phenomenon. This behaviour can also be noticed for the mixed, weak uppeak and weak down peak conditions. That implies although a more or less balanced up- and down- traffic can boost *HC*, the cost is an increase in *MTT* where passengers need to spend more time in the elevator on average. Having said that, even when *P* has grown from 10 to 20, i.e. an increase by 100%, the *MTT* has not grown by the same ratio. Under normal and extreme uppeak and down peak conditions, the *MTT* starts to decrease as *P* is increasing.

It is interesting to note that as *P* is getting larger and larger, both *RTT* and *MTT* tend to get saturated. But *HC* can further increase, though with a much lower rate as compared with that when *P* is small. That explains why *HC*/*RTT* can slightly increase even when *P* is approaching 40, four times the *CC*. The reason is that the exact *HC* that one elevator can provide within one round trip very much depends on the distribution of the landing and car calls around the building, not only on *P*, as illustrated by Table 1. If most car calls are short trips and landing calls widely distributed, say from 1/F to 4/F, from 4/F to 5/F, from 5/F to 6/F, and so on, the *HC* could be rather high. Hence, though the *HC* may get saturated for some cases, there is room for growth for other cases, which may explain why on average, *HC* can continue to rise, but gradually slower and slower. In practice, usually, there is more than one elevator in one bank while the supervisory control can balance the dispatching of different elevators to serve different landing calls.

5 CONCLUSIONS

It is conventional that system design of the elevator industry starts with a traffic analysis on pure incoming traffic patterns during the uppeak period by calculation to estimate the round trip time (*RTT*), 5-minute handling capacity (*HC*), uppeak interval (*UPPINT*), average waiting time (*AWT*), and average transit time (*ATT*) respectively. This process is followed by in-depth real time computer simulation on selected scenarios to arrive at the final design, as recommended by ISO 8100-32: 2020 for office, hotel and residential buildings. Over the past two decades, it has been found that pure incoming traffic is no longer the dominant traffic pattern of a modern office building and a typical one consists of a mixture of incoming, outgoing and interfloor modes. That led to the development of the universal traffic analysis approach by working on an origin-destination matrix where the Universal *RTT* and *HC* etc. are computed.

Under a pure incoming traffic condition, the total demand (*P*) of one round trip of an elevator cannot go beyond the contract capacity (*CC*) as conventionally assumed. Based on the proposed theoretical concept of a previous study and the in-depth simulation results of this article, it is shown that a system usually has room for handling more passengers for *P* to go beyond *CC*, in particular, during a down-journey of an uppeak condition or the up-journey of a down peak condition. In other words, the system has potential to increase *HC* during a journey opposite to the current traffic mode.

By this argument, it is shown by simulation that during a more or less balanced up- and down-traffic mode, *HC* can easily approach $P = 2\ CC$. Having said that, under most conditions, *P* can easily go beyond *CC* except under a pure incoming or pure outgoing traffic mode. It is also shown in this article that *HC* accomplishment is more constrained under a pure incoming mode. And that may explain why over the decades, pure incoming traffic has been the focus of designers because it may be the worst case to handle, and the safety margin of design is higher. If the system is well designed to accommodate pure incoming traffic, it may be able to handle other traffic patterns. But if the safety margin is always higher, the system may be oversized, thus wasting resources. Having said that, lunch peaks may consist of heavy incoming and outgoing passengers and these could be the critical headache.

The parameter, *HC*/*RTT*, was proposed to indicate whether the number of passengers handled could be increased by keeping a relatively shorter round trip time. And it is found that pure interfloor traffic, without any incoming or outgoing passengers, favours a higher *HC*/*RTT* when *P* is getting higher. Having said that, though a more balanced up- and down- traffic can boost *HC*, the cost is an increasing mean transit time (*MTT*).

Therefore, an optimal system design needs to consider a compromise between short *RTT*, short interval (*INT*), short *AWT*, high *HC* and short *MTT*. It seems that such optimal design may make use of the small range from $P > CC$ until $P \leq 2\ CC$. At this moment, there is no formula in the world that allows all these be analytically studied by calculation. And if real time dispatcher-based computer simulation is to be carried out, a consideration of so many different cases may imply a very intensive computational load. Therefore, Monte Carlo simulation using the **PDFOD** and **CDFOD** matrices may provide a balanced solution between the two, demonstrating the usefulness of Monte Carlo simulation in system design. Moreover, it is shown in this article that the total passenger demand, rather than a probability distribution function alone adopted in the traditional RTT calculation, needs to be an important input element to the calculation that can easily be applied by practitioners. In other words, this approach may allow Monte Carlo simulation to be easily incorporated into popular traffic analysis software using the same inputs as other techniques, while the results could be cross compared with those obtained by dispatcher-based simulations [19].

Furthermore, although *HC* may give some indication of the performance of the overall elevator service, *AWT*, the average waiting time of passengers, should be another which may perhaps be more important. *AWT* obviously tends to increase significantly when *P* is getting larger. And this could be a further study consequent to what has been reported in this article.

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