The Passenger Transfer Efficiency Coefficient (PTEC) for Double Deck Elevators under Incoming Traffic Conditions

Lutfi Al-Sharif, Enas AlOsta, Noor Abualhomos, Yazan Suhweil

lal-sharif@theiet.org

Mechatronics Engineering Department, School of Engineering
The University of Jordan, Amman 11942, Jordan

Abstract. One of the sources of efficiency in the operation of double deck elevators is the simultaneous transfer of passengers into and out of the elevator cars, thus leading to a reduction in the value of the round trip time, and thus an increase in the handling capacity.

However, due to the randomness of passenger destination selections, this reduction is not optimal. This paper presents this phenomenon as an efficiency coefficient, denoted as the Passenger Transfer Efficiency Coefficient (PTEC) and is representative of the time taken by passengers to alight from the double deck elevator.

PTEC is mainly applicable to passengers alighting, rather than passengers boarding. This is true in the case of a single pair of entrances. For the case of multiple pairs of entrances, the PTEC applies to both alighting and boarding operations.

A set of equations are derived in order to calculate the PTEC. The results from the equations are verified using the Monte Carlo simulation method. The method of stepwise verification has been used in order to verify the equations.

Nomenclature

L the number of elevators in the group
N the total number of floors above the pair of main entrances
P the number of passengers per deck
P_e the number of passengers for the even deck
P_o the number of passengers for the odd deck
PTEC passenger transfer efficiency coefficient
S is the expected value of the number of stops in a round trip
t_p the passenger alighting or boarding time in seconds
U is the total building population in persons
U_i is the population of the ith floor in persons
U_e is the total population of the even floors in persons
U_o is the total population of the odd floors in persons

1   INTRODUCTION

Double deck elevators offer a very efficient means of moving people within buildings ([1], [2] and [3]). By placing two conventional single deck elevators one on top of the other and attaching them rigidly, shaft space is saved. Passengers board both decks at the same time, whereby passengers heading to an odd floor board the lower deck and passenger heading to the even floors board the upper deck. The elevator then moves two floors at a time. Once a stop is made, passengers alight simultaneously from the upper and lower decks to the even and odd destination floors respectively.

There are three sources of efficiency that arise from using double deck elevators:

1. For incoming traffic, the effective number of stops is reduced due to the fact that the potential number of floors is halved ($N/2$ instead of N). This reduces the value of the round trip time and thus increases the handling capacity.
2. The passenger boarding and alighting time is reduced due to simultaneous boarding and alighting of passengers on the two decks.
3. Due to the fact that the two elevator cars are mounted on top of each other, the elevator handling capacity is increased without a major increase in the core space usage.

Double deck elevators are mainly used in two broad applications ([4], [5]):

1. They are as effective as shuttles between the ground floor and sky lobbies. The efficiency arises from the fact that there are only two stops (or three stops) thus reducing the value of the round trip time. The elevator car capacity in such situations is made relatively large.
2. They are currently increasingly being used in low and medium rise buildings in cases where the floor populations are relatively high. For example, double deck elevators can be very effective in buildings with more than 250 persons per floor (examples are given in [6]).

The use of double decker lifts has an impact on the value of the round trip time, by reducing it. The reduction in the value of the round trip time leads to a shorter round trip and hence an increase in the number of passengers that the elevator system can transport in five minutes. This leads to an increase in the handling capacity. This is one of the main benefits of using double deck elevators, whereby the other is the reduction in core space.

Barney [4] presents a comprehensive list of the double decker installation around the world and their applications. Siikonen [7] presents the equations for the expected number of stops (S) and the highest reversal floor (H) for the case of equal and unequal populations and derives a parameter for the passenger transfer efficiency. Genetic algorithms have been widely applied in elevator traffic control systems examples of which can be found in ([7], [9], [10] and [11]). More specifically, Sorsa *et al.* [8] use genetic algorithms to achieve optimal control of double deck elevators.

Two pieces of work on double deck elevator formulae are given by Kavounas [12] and Peters [13] and [14]. Kavounas derives a formula for the highest reversal floor and the expected number of stops. Peters [13] and [14] presents formulae for the general case under Poisson arrival conditions. However, it is difficult to carry out comparison with the results in these papers as they do not present any closed form equations (instead, calculations that they present are iterative and require computer implementation).

The published research in the area of double deck elevator does not address the following two points:

1. No mathematical formula has been derived for the passenger transfer efficiency (i.e., the quantification of the benefits of simultaneous passenger alighting at the destination floors). The main aim of this paper is to derive a formula for the passenger transfer efficiency. This is critical in enabling the correct calculation of the round trip time ([15], [16], [17]).

2. No verification has been carried out to ensure the accuracy of the derived equations. The derived equations presented in this paper have been verified using the Monte Carlo Simulation method (MCS).

Section 2 introduces some necessary assumptions and numbering conventions used in this paper. Section 3 introduces the concept of the passenger transfer efficiency and derives equations for the PTEC for the cases of equal floor populations. Section 4 discusses a similar parameter presented by Siikonen. Section 5 presents a numerical example to understand the effect of the number of passengers, P, and the number of floors, N, on the coefficient. Conclusions are drawn in section 6.

2   ASSUMPTIONS AND NUMBERING CONVENTIONS

In this section, some of the assumptions are clearly stated as well as the numbering notation for the building. It is necessary to clearly state some of the assumptions that will be made within this paper and provide some background required for the derivations.

Throughout this paper, it will be assumed that a single pair of entrances is used for boarding. There is only one pair of entrance floor, which is in effect a single entrance scenario. Each passenger can only enter the building through one floor: the odd entrance for odd destination occupant floors and the even entrance for even destination occupant floors.

It will also be assumed that all traffic is incoming traffic. Incoming traffic is traffic that originates at an entrance floor and terminates at an occupant floor. This is not an unreasonable assumption to make. The reason for this is that double deck elevators are usually operated in double deck mode under incoming traffic conditions during which they are most efficient. The design of double deck elevators is still based on the morning incoming traffic (up peak traffic). It is possible to operate double deck elevators in single deck mode outside peak hours. Under single deck mode, one of the decks is deactivated and the other deck serves passengers as a single deck.

It is also necessary to define the concept of a twin pair of floors, one of which is odd and the other even. This concept is critical to all the derivations that will follow in this paper. A twin pair of floors is, as the name implies, *consecutive* floors at which the double deck will make a *simultaneous* stop and deliver passengers. For brevity in the analysis below, the pair of twin floors will be simply referred to as twin floors. The lower floor will be assumed to be the odd floor and given the subscript o for odd; the upper floor will be assumed to be the even floor and given the subscript e for even. A general overview of the arrangement of a building that is served by double deck elevators is shown in Figure 1.
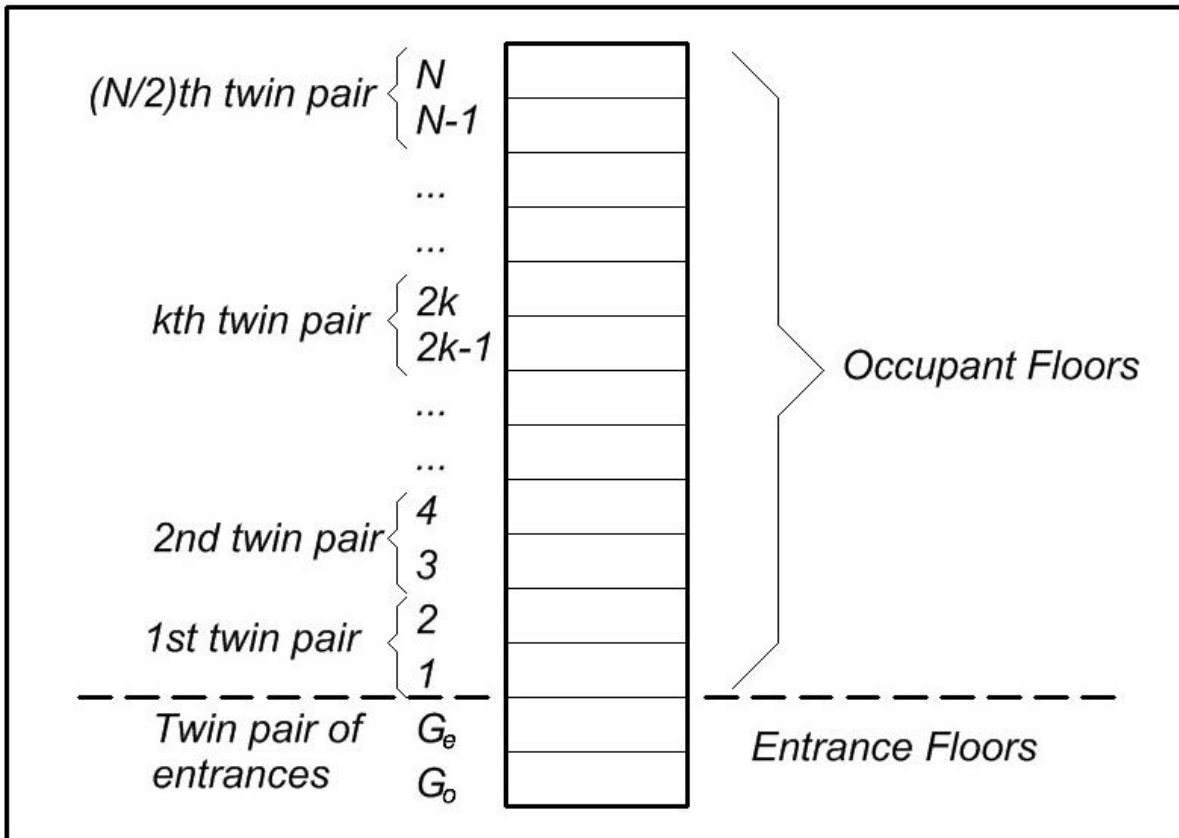
Figure 1: General overview of a building served by double deck elevators, showing the numbering convention used.

It will also be assumed that the number of occupant floors is even. This is the most efficient arrangement. However, some notes are given in [18] as to how the case of an odd number of occupant floors can be addressed.

3   DERIVATION OF THE FORMULA FOR THE PASSENGER TRANSFER EFFICIENCY COEFFICIENT

The passenger transfer efficiency coefficient (PTEC) is unique to double deck elevator systems (or to multiple deck systems in general). It is a measure of the efficiency of the passenger transfer time (i.e., boarding and alighting). There are two phases of passenger transfer in any elevator: boarding time and alighting time.

Based on a single pair of entrances, passenger transfer efficiency during boarding is not a concern (noting that it is assumed that all the traffic is incoming only). It is assumed that all P passengers for each deck (i.e., the upper deck and the lower deck) start boarding at the same time and finish boarding at the same time. Thus there is no wasted time and full efficiency is automatically attained.

However, the issue of passenger transfer efficiency is more of a concern during alighting. As there are many occupant pairs of floors (that will act as destinations for passengers) it is likely that different numbers of passengers are destined for the odd and even floors of the same stop. The most efficient scenario would take place in a double deck elevator when an equal number of passengers from the two decks alight at the same stop. In this case it can be stated that there is no wasted time, as there is no wasted waiting time at one deck while one or more passengers are alighting from the other deck.

For example, if at one of the double decker stops, five passengers alight from the upper (even) deck and one passenger alights from the lower (odd) deck, then the actual alighting time is equal to the time required for the five passenger to alight from the upper deck. The difference between the numbers of passengers intending to alight at this stop has effectively caused a loss of time. Had the number of passengers intending to alight been equal (i.e., three passengers for the upper deck and the three passengers for the lower deck) then the total alighting time would have been only equal to the time required for three passengers to alight, resulting in a saving equal to the time required by two passengers to alight. It is this efficiency (or inefficiency) that this parameter aims to capture. The formula for the case of equal floor population will be derived in this section.

In order to derive a formula for the *PTEC*, it is necessary to find an expression for the probability of the number passengers destined for the odd floor of the twin pair of floors being equal to i and the passengers destined for the even floor of the twin pair of floors being equal to j.

Each of these events shall be denoted as A and B respectively, as follow:

A is the event under which i passengers are destined for the odd floor of the pair of twin floors.

B is the event under which j passengers are destined for the even floor of the pair of twin floors.

For each of these events, the probability distribution function is effectively a binomial distribution (i.e., a passenger can either head or not to a certain floor). For each deck, it is assumed that P passengers will board the deck in each round trip at the main entrance.

It is now necessary to find the probability of i specific passengers going to a floor. This implies that other P-i passenger did not go to that floor. The probability of the joint event is the product of the two probabilities:

$$\Pr(i_s \text{ } going \text{ } to \text{ } a \text{ } floor \text{ } and \text{ } (P - i)_s \text{ } not)$$
$$= \left(\frac{2}{N}\right)^i \cdot \left(1 - \frac{2}{N}\right)^{P-i} \tag{1}$$

This can then be applied to the odd floor of the twin floors and the even floor of the twin floors as shown in the two equations below. (It is implied that if i specific passengers go the floor then P-i passengers will not without the need to explicitly state it in the formula).

$$\Pr(P_o = i_s) = \left(\frac{2}{N}\right)^i \cdot \left(1 - \frac{2}{N}\right)^{P-i} \tag{2}$$

$$\Pr(P_e = j_s) = \left(\frac{2}{N}\right)^j \cdot \left(1 - \frac{2}{N}\right)^{P-j} \tag{3}$$

As the two events are independent, then the combined event whereby i specific passengers head to the odd floor and j specific passengers head to the even floor of the twin pair of floors is:

$$\Pr(P_o = i_s \cap P_e = j_s) = \left(\frac{2}{N}\right)^i \cdot \left(1 - \frac{2}{N}\right)^{P-i} \cdot \left(\frac{2}{N}\right)^j \cdot \left(1 - \frac{2}{N}\right)^{P-j} \tag{4}$$

In the terminology used in the derivations so far the term *specific* passengers has been used. This emphasises the fact that the derivation involves a specified set of i passengers and a specific set of j passengers. But the event will take place if any combination of i passengers in the odd deck are destined for the odd twin floor and if any combination of j passengers in the even deck are destined for its twin even floor. There are a number of different ways in which i passengers can be picked

out of a total of P passengers and a number of different ways in which j passengers can be picked out of P passengers in even deck. These are in effect combinations and standard formula for combinations can be used as shown in the equation below.

$$\Pr(P_o = i \cap P_e = j)$$
$$= {}_PC_i \cdot \left(\frac{2}{N}\right)^i \cdot \left(1 - \frac{2}{N}\right)^{P-i} \cdot {}_PC_j \cdot \left(\frac{2}{N}\right)^j \cdot \left(1 - \frac{2}{N}\right)^{P-j} \tag{5}$$

This equation is now used to populate a dedicated matrix as shown below. The row index represents number of passengers heading to the odd floor of the twin pair of floors and the column index represents the number of passengers heading to the even floor of the twin pair of floors. The matrix is a $P+1$ by $P+1$ square matrix, as it is important to include the possible case whereby there are no passengers alighting from either deck.

$$
\begin{bmatrix}
\Pr(0_o 0_e) & \Pr(0_o 1_e) & \dots & \Pr(0_o j_e) & \dots & \Pr(0_o P-1_e) & \Pr(0_o P_e) \\
\Pr(1_o 0_e) & \Pr(1_o 1_e) & \dots & \Pr(1_o j_e) & \dots & \Pr(1_o P-1_e) & \Pr(1_o P_e) \\
\vdots & \vdots & \dots & \vdots & \dots & \vdots & \vdots \\
\Pr(i_o 0_e) & \Pr(i_o 1_e) & \dots & \Pr(i_o j_e) & \dots & \Pr(i_o P-1_e) & \Pr(i_o P_e) \\
\vdots & \vdots & \dots & \vdots & \dots & \vdots & \vdots \\
\Pr(P-1_o 0_e) & \Pr(P-1_o 1_e) & \dots & \Pr(P-1_o j_e) & \dots & \Pr(P-1_o P-1_e) & \Pr(P-1_o P_e) \\
\Pr(P_o 0_e) & \Pr(P_o 1_e) & \dots & \Pr(P_o j_e) & \dots & \Pr(P_o P-1_e) & \Pr(P_o P_e)
\end{bmatrix}
$$

Where: $\Pr(i_o j_e)$ is the probability that i passengers go to the odd floor and j passengers go to the even floor.

It is worth noting the following points about the different areas of this matrix:

1. The diagonal elements of the matrix represent the cases where the numbers of passengers destined for each of the odd and even floors of the twin are equal. For example, $\Pr(3_o 3_e)$ is the probability of three passengers being destined to the odd floor of the twin pair of floors and the three passengers destined to the even floor of the same twin pair of floors.
$$P_e = P_o$$

    In this case, the actual passenger transfer time is the time required for either deck as they are equal (i or j). This is the most efficient case as there is no loss of efficiency in passenger transfer.

2. The upper triangle of the matrix (i.e., above the diagonal as shown in the figure below) represents the cases where the number of passengers destined for the even twin floor is larger than the number of passengers destined to the odd floor of the twin pair of floors. In other words:
$$P_e > P_o$$

In this case, the actual passenger transfer time is the time required for the even deck passengers to alight, which is the column index, j. In this case, there is a loss of efficiency in passenger transfer, proportional to the difference between i and j.

3. The lower triangle of the matrix (i.e., below the diagonal) represents the cases where the number of passengers destined to the odd twin floor is larger than the number of passengers destined to the even twin floor. In other words:

$$P_o > P_e$$

In this case, the actual passenger transfer time is the time required for the odd deck passengers to alight, which is the row index, i. In this case as well, there is a loss of efficiency in passenger transfer, proportional to the difference between i and j.

$$
\begin{bmatrix}
\Pr(0_o 0_e) & \Pr(0_o 1_e) & \cdots & \Pr(0_o j_e) & \cdots & \Pr(0_o P-1_e) & \Pr(0_o P_e) \\
\Pr(1_o 0_e) & \Pr(1_o 1_e) & \cdots & \Pr(1_o j_e) & \cdots & \Pr(1_o P-1_e) & \Pr(1_o P_e) \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
\Pr(i_o 0_e) & \Pr(i_o 1_e) & \cdots & \Pr(i_o j_e) & \cdots & \Pr(i_o P-1_e) & \Pr(i_o P_e) \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
\Pr(P-1_o 0_e) & \Pr(P-1_o 1_e) & \cdots & \Pr(P-1_o j_e) & \cdots & \Pr(P-1_o P-1_e) & \Pr(P-1_o P_e) \\
\Pr(P_o 0_e) & \Pr(P_o 1_e) & \cdots & \Pr(P_o j_e) & \cdots & \Pr(P_o P-1_e) & \Pr(P_o P_e)
\end{bmatrix}
$$

The next step is to find the expected maximum number of passengers alighting. Use will be made of the three areas of the matrix: one equation will be developed for the upper triangle of the matrix, one for the diagonal of the matrix and one for the lower triangle of the matrix.

The expected value of the maximum number of passengers alighting at each stop for the even number of passenger can be found by summing the product of the probability of each number of passengers alighting by their number from the upper triangle of the matrix. The limits of the summations ensure that the number of passengers alighting on the upper (even) deck is larger than the passengers alighting from the lower (odd deck). *Note that the operator is the expected value or the average.*

$$
\mathrm{E}(P_e)\big|_{P_e > P_o} = \sum_{j=1}^{P} \sum_{i=0}^{j-1} \left(j \cdot \left({_P}C_i \cdot \left(\frac{2}{N}\right)^{i} \cdot \left(1 - \frac{2}{N}\right)^{P-i} \cdot {_P}C_j \cdot \left(\frac{2}{N}\right)^{j} \cdot \left(1 - \frac{2}{N}\right)^{P-j} \right) \right) \tag{6}
$$

The same is repeated for the lower triangle of the matrix as shown in the equation below.

$$
\mathrm{E}(P_o)\big|_{P_o > P_e} = \sum_{i=1}^{P} \sum_{j=0}^{i-1} \left(i \cdot \left({_P}C_i \cdot \left(\frac{2}{N}\right)^{i} \cdot \left(1 - \frac{2}{N}\right)^{P-i} \cdot {_P}C_j \cdot \left(\frac{2}{N}\right)^{j} \cdot \left(1 - \frac{2}{N}\right)^{P-j} \right) \right) \tag{7}
$$

Equations (6) and (7) contain two terms: one involves the number of passengers alighting at the even floor and the other the number of passengers alighting at the odd floor.

As for the diagonal terms, there is only one summation and the index runs from 1 to P (the case where both P_e and P_o are zero is disallowed, as there would not be a stop in the first place if there are no passengers heading to either floor of the twin).

$$E(P_e)|_{P_e=P_o} = \sum_{i=1}^{P}\left(i \cdot \left({}_PC_i \cdot \left(\frac{2}{N}\right)^i \cdot \left(1-\frac{2}{N}\right)^{P-i}\right)^2 \right) \tag{8}$$

Combining all the three cases, it is possible to evaluate the expected value of the maximum number of passengers alighting per twin pair of floors. The expected value is the summation of the three contributions to the expected value in the three cases.

$$E(P_{max})|_{\text{twin}} = E(P_e)|_{P_e>P_o} + E(P_o)|_{P_o>P_e} + E(P_e)|_{P_e=P_o} \tag{9}$$

However, there are $N/2$ twin number of floors, where N is the total number of floors above the main entrance. Thus the expected value of the maximum number of passengers alighting in a round trip is:

$$E(P_{max})|_{\text{RTT}} = \frac{N}{2} \cdot \left(E(P_e)|_{P_e>P_o} + E(P_o)|_{P_o>P_e} + E(P_e)|_{P_e=P_o} \right) \tag{10}$$

Finally, the PTEC is the ratio between the expected value of the maximum number of passengers alighting in each round trip divided by the number of passengers per deck.

$$\text{PTEC} = \left(\frac{N}{2 \cdot P}\right) \cdot \left(E(P_e)|_{P_e>P_o} + E(P_o)|_{P_o>P_e} + E(P_e)|_{P_e=P_o} \right) \tag{11}$$

The equations derived above for the value of PTEC have been rigorously verified using the Monte Carlo simulation method ([19], [20], [21]) with excellent agreement. More details of numerical examples can be found in [18].

It is expected that the value of the PTEC will improve (i.e., become smaller and more efficient) under destination group control ([22], [23], [24], [25], [26], [27]). This is the current of future research whereby the formula is re-derived under destination group control conditions.

PTEC can range from 1 to 2. It attains it minimum value of 1 when all passengers alight simultaneously at the destination floors. It attains its maximum value of 2 when passenger only alight from one deck at every stop.

4   THE COEFFICIENT PRESENTED BY SIIKONEN

Siikonen derived a coefficient for passenger transfer loading [7]. The derivation will be presented below:

The probable number of stops equals to:

$$S_d = \frac{N}{2} - \sum_{k=1}^{\frac{N}{2}}\left(1-P_{2k,d}\right)^{2P} \tag{12}$$

Where $P_{2k,d}$ is the probability of passenger going to $2k$-1 or $2k$ floor.

$$P_{2k,d} = \frac{U_{2k-1}}{U} + \frac{U_{2k}}{U} \tag{13}$$

The probable number of stops for upper deck only equals to:

$$S_s = \frac{N}{2} - \sum_{j=1}^{\frac{N}{2}} \left(1 - P_{2j,s}\right)^P \tag{14}$$

Where $P_{2j,s}$ is the probability of passenger going to even floor.

$$P_{2j,s} = \frac{U_{2j}}{U_e} \tag{15}$$

Then, the total passenger transfer time will equal:

$$= \left(2 - \frac{S_s}{S_d}\right) * t_p \tag{16}$$

This equation assumes that inefficiencies will occur in both alighting and boarding, whereas in this paper the authors have assumed that inefficiency only takes place in alighting and not in boarding. Siikonen also assumes that the population of every twin pair of floor is equal (i.e., the population of the even floor of the twin pair is equal to the population of the odd twin pair) so that the numbers of stops for single deck for odd and even are equal.

5   NUMERICAL EXAMPLE

In order to gain a numerical appreciation of the range of values of the coefficient (i.e., the PTEC), a numerical example is presented in this section for a realistic range of values for P and N. As discussed earlier in this paper, the coefficient will range from the smallest possible value of 1 (representing full efficiency in passenger alighting from both decks) to the maximum possible value of 2 (representing zero efficiency in passenger alighting from both decks).

Assuming a building with equal floor populations and equal capacity for both decks and an even number of floors above the pair of main entrances, the PTEC was calculated for a range of value of P and N. The results are shown in Table 1.

Table 1: The value of the PTEC for a number of buildings.

P (each deck)	N (number of floors above the main entrance)					
	10	12	14	16	18	20
10	1.3474	1.3848	1.4187	1.4485	1.4763	1.5012
13	1.3062	1.3411	1.3713	1.3992	1.4243	1.4474
17	1.2699	1.3001	1.3274	1.3521	1.375	1.3958
20	1.2486	1.278	1.3029	1.3262	1.3475	1.3679
26	1.2186	1.2445	1.2666	1.2875	1.3069	1.3247

As can be seen from the results, the value of the PTEC ranges from around 1.2 up to 1.5. As the number of passengers per deck increases, the efficiency increases (with smaller value of PTEC) as

expected. Moreover, as the number of floors above the main entrances increases, the efficiency decreases (with a larger value of PTEC) as expected.

6   CONCLUSIONS

A new parameter has been introduced that measures the efficiency of the passenger transfer time denoted as the PTEC (passenger transfer efficiency coefficient). It represents how efficient the transfer of passenger is when alighting at the destination floors. The PTEC can be used in the calculation of the round trip time whereby it provides an accurate measure of the passenger transfer time. In general, the round trip time equation contains a passenger transfer element that accounts for the time taken up by passenger in boarding and alighting. In this case, the PTEC can be used to amend the time required by passenger to alight at their destinations by taking into consideration the time saving that results from simultaneous passenger alighting from both decks.

The PTEC has been derived for the case of equal floor populations. The derived equations have been verified using the Monte Carlo Simulation method with excellent agreement. A similar coefficient presented by Siikonen is also studied assuming equal alighting probabilities for even and odd decks. A numerical example is given for a number of buildings in order to show the effect of the number of passengers per deck (P) and the number of floors above the pair of main entrances (N) on the value of the coefficient. It is shown that the value of the coefficient increases with the increase in N and decreases with the increase in P.

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BIOGRAPHICAL DETAILS

Lutfi Al-Sharif is currently professor of building transportation systems at the Mechatronics Engineering Department at the University of Jordan, Amman, Jordan. His research interests include elevator traffic analysis and design, elevator and escalator energy modeling and simulation and engineering education.

Enas AlOsta, Noor Abualhomos and **Yazan Suhweil** all graduated from the department of mechatronics engineering at the University of Jordan, Amman, Jordan in 2017.