Using the Inter-Linked Monte Carlo Simulation Method (iL-MCS) to Calculate the Value of the Elevator Round Trip Time to Reflect the Random Nature of Passenger Destinations

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Abstract. The Monte Carlo Simulation method (MCS) has been successfully used to find the value of the elevator round trip time under general traffic conditions. It has also been extended to find the value of the round-trip time under destination group control. This paper extends the application of the method by introducing the so-called "interlinked Monte Carlo Simulation" method (iL-MCS). In the conventional MCS method, the trials are not linked, and each trial is completely independent of the other trials. The new suggested method (iL-MCS) links the trials such that the end conditions of one trial affect the initial conditions of the following trial. This "interlinking" allows the method to reflect the effect of the random passenger destinations on the value of the round-trip time. It can even be extended to quantify the effect of elevator bunching on the value of the round-trip time and hence the loss in handling capacity due to the effects of elevator bunching. Examples will be coded in MATLAB and presented to illustrate the method and its results.

1. INTRODUCTION

The elevator round trip time has for a long time formed the basis of sizing and selecting the number and speed of elevators in a building [1] following the assessment of demand [2]. Even with the advent of simulation, most designers still use the round-trip time as the basis for the initial phase of the design based on calculation and then follow it up with simulation runs to refine the final design.

The calculation of the value of the round trip time has traditionally been based on using an equation that was developed and expanded in the 1980s [3] which relies on the elevator kinematic equations ([4], [5]). The main drawback of this equation is that it is only applicable and correct in a special set of conditions such as incoming traffic, independent passenger decisions, rated speed attained in one floor jump and a single entrance. A number of researchers have attempted to extend the application of this equation to more general cases ([6], [7], [8]). An attempt was also made to extend the equation to accurately incorporate all of these special conditions [9].

One of the most important successes in this area was the application of the Monte Carlo simulation method to find the value of the round-trip time under incoming traffic conditions [10] and then under general traffic conditions [11]. It was also used to find the value of the average travelling time [12]. In one of the latest papers, it was used to evaluate the round-trip time for hypothetical traffic systems ([13], [14], [15]) and even under destination group control [16].

In all these papers that used the Monte Carlo simulation to find the value of the round-trip time, the trials were completely independent. Each trial was kept separate from the preceding and the succeeding trials. This paper introduces the concept of interlinking the consecutive trials in order to better reflect the randomness in the elevator traffic system. Specifically, this paper *interlinks* the trials in order to reflect the effect of the variability in the value of the round-trip time that is caused only by the randomness of the passenger destination.

It is worth mentioning that this paper will not take into consideration the randomness in the arrival times of the passengers (assumed to follow a Poisson distribution). This would be the scope of a future paper.

The way in which the Monte Carlo simulation has been applied to the evaluation of the round-trip time has been based on generating random passenger origins and destinations. These origins and destination are then used in order to calculate the exact value of the round trip time for this trial (or scenario) by calculating the kinematics of movement of the car to get to the required floors, the door opening and closing time, and the passenger transfer time into and out of the car. This value of the round-trip time is stored in an array. The process is repeated for many trials (denoted as n, say 10 000 trials). The value of the round-trip time for each trial (or scenario) is stored in the same array. At the end of the n trials, the average value of the round-trip time is taken as representative of the true value.

A similar process will be followed in this paper, but with the difference that the number of passengers generated in each trial is not constant, but dependent on the previous value of the round-trip time. The car capacity will be assumed to be limited, thus better reflecting the reality of the fluctuations in the value of the load in the elevator car.

The second section will identify the two sources of randomness in elevator traffic systems. The third section takes one of these sources of randomness and further discusses the two-way complex inter-dependence between the number of passengers boarding the elevator car and the value of the resultant round-trip time. The fourth section evaluates the value of the round-trip time under interlinked Monte Carlo simulation conditions, assuming an unlimited car capacity. "Unlimited car capacity" means that whatever the number of passengers waiting at the landing can board the car and are not restricted by the physical car capacity. The fifth section shows that the analysis would always converge to the same average value of the round-trip time regardless of the starting conditions. The sixth section explores the effect of limiting the car capacity on both the value of the passengers in the car and the overall handling capacity. Conclusions are drawn in the seventh section.

2. THE TWO SOURCES OF RANDOMNESS IN ELEVATOR TRAFFIC SYSTEMS

The two sources of randomness in elevator traffic systems are the following:

1. The first source of randomness in the arrival times of the individual passengers. It has long been recognized that the arrival of passengers for service follows a Poisson distribution (more precisely, the number of passengers arriving in a specified period of time follows a Poisson distribution, and this random variable is a discrete random variable). It is more common to model this process by examining the inter-arrival time between consecutive passengers, which follows an exponential distribution, whereby the random variable is a continuous random variable. This source of randomness is not considered in this paper. For simplicity, the inter-arrival time is assumed to be constant.

2. The second source of randomness in elevator traffic systems is the randomness of the passenger origin and destination floors. In the general case, it is assumed that the passenger origin and destination selections are independent. When the building under consideration has a single entrance and the type of traffic is incoming only, the origin floor is the same for all passengers and the source of randomness is the passenger destination floors. Each passenger is assumed to select a destination based on the probability density function for the floor destinations, which is based on the number of occupants in each floor.

These two sources are the source of all randomness in the elevator traffic system, and any other display of randomness in the elevator has its roots in one or both of these two sources. For example, the variability of the round trip is caused by the random passenger destinations (2nd source above) and the variability of the number of passengers boarding the elevator car (which is caused by both the first and second sources above).

It is also worth remembering that the variability of the round-trip time for each elevator will lead to the time between the successive arrivals of the elevators at the landings being variable, a phenomenon known as bunching ([17], [18]). It is widely accepted that bunching can lead to the loss of handling capacity and the increase in the passengers waiting time. In extreme, cases, bunching can lead to the reversal of the sequence of elevator movements around the building (i.e., with four elevators in the group, and assuming they start in the sequence of A, B, C and D, this could later become A, C, B, D).

In this paper, only the second source of randomness is modelled (and more specifically, the passenger destinations only, as the building under consideration has only one entrance and the type of traffic is incoming only). Its effects on the variability in the value of the round-trip time, number of passengers boarding the elevator car and the passengers left queuing behind at the landing are all explored.

The other source of randomness is not considered in this paper and will be the subject of a future paper.

3. THE COMPLICATED INTER-DEPENDENCE BETWEEN THE NUMBER OF PASSENGERS BOARDING THE CAR IN A ROUND TRIP AND THE VALUE OF THE ROUND TRIP TIME

The randomness of the passenger destinations result in the variability of the value of the round-trip time. When the round-trip time varies, this means that the elevator car will take longer than normal or shorter than normal to return to the main entrance (or to any landing) for the next round-trip. This variability means that more passengers will have accumulated at the landing (when the round trip time is longer than its average value) or fewer passengers would have accumulated at the landing (when the round-trip time is shorter than its average value). If the elevator car has unlimited capacity, then it is assumed that the elevator car can take all of these passengers. This variability in the number of passengers boarding the car will then, in turn, lead to the variability of the value of the round-trip time….and so on. This inter-dependence between the number of passengers boarding the car in each round trip and the value of the round trip time is best represented by using the Inter-linked Monte Carlo simulation, where the value of the round trip time in each trial is used to determine the number of passengers in the following round is neatly capture by consecutive numerical trials.

So this is a two way effect: The increase in the number of passengers boarding the elevator car in a round trip will generally increase the value of the round trip; and the increase in the value of the round trip means that more passengers "accumulate" waiting at the landings waiting to board that elevator car. The decrease in one variable will also then lead to a decrease in the other.

However, this vicious cycle is broken by the randomness of the passenger destinations. For example, even if the number of passengers in a round trip is large, they could all be heading to coincident lower floors in the building leading to a smaller value of round-trip time. Alternatively, even if the number of passengers is small in a round-trip, they could all be heading to non-coincidental floor in the upper part of the building, leading to a larger value of the round-trip time.

4. THE NUMBER OF PASSENGERS IN THE CAR IN EACH TRIAL ASSUMING UNLIMITED CAR CAPACITY

In this section, the car capacity is assumed to be unlimited. The consequence of this simplifying assumption is that no passengers are left behind in each round trip and thus no passengers need to be "carried-over" to the next round trip. In section 6, this assumption is removed, and the effect of the limited car capacity is further explored, which results in passengers being left behind at the landing and being "carried-over" to the next round-trip trial. It is interesting to note that adding this feature to the Monte Carlo simulation method, represents an action that moves the system nearer to the characteristics of discrete time-simulation (or time dependent simulation).

Under the conventional Monte Carlo simulation trials, it is assumed that the number of passengers is constant in each trial (10 passengers in this case). In order to allow the reader to have a visual base to compare the following graphs to, this trivial assumption has been shown in Figure 1 assuming constant passenger arrival rate.

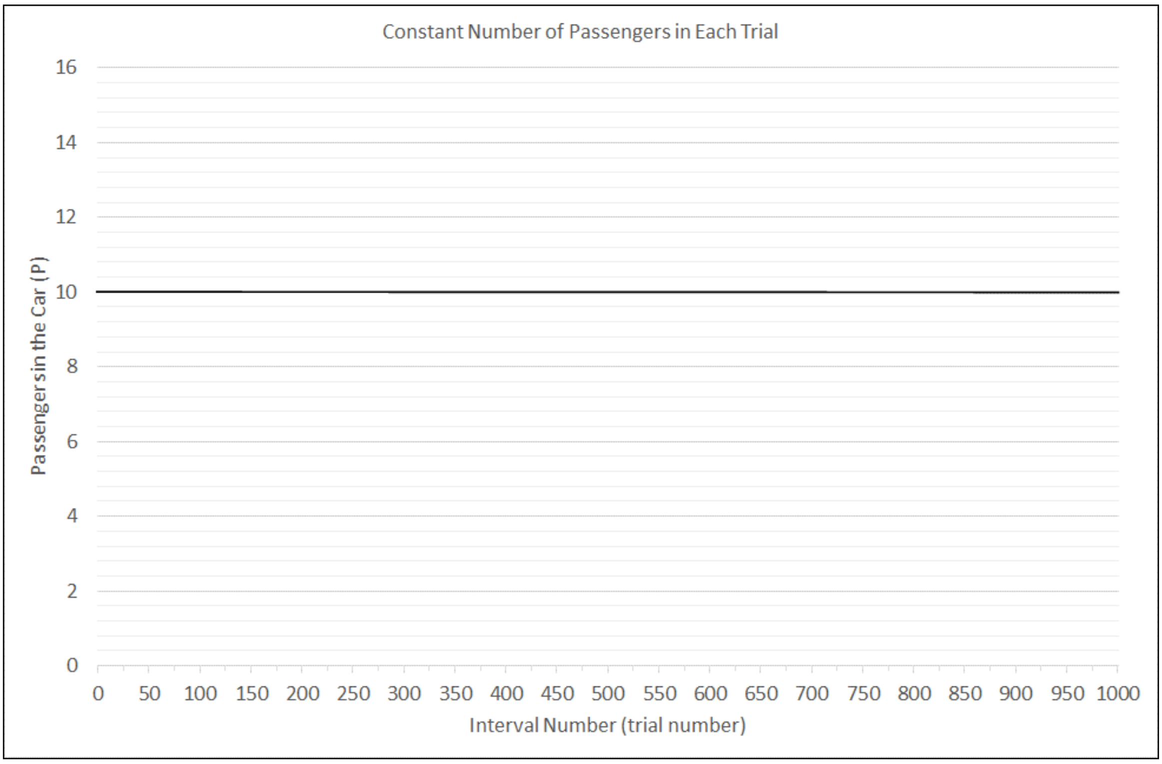

Figure 1: The number of passengers in the car is constant in each trial.

The next figure shows how "interlinking" the consecutive Monte Carlo simulation trials alters the value of the passengers boarding the elevator in each round trip. The value of the passengers boarding the elevator car in each round trip only depends on the value of the round trip in the previous trial. It is remarkably interesting to note the average value of passengers remains around 10 (which is the original value on which the building was designed and the number of elevators base). This phenomenon can also be seen in the next section, where the value of passengers always "gravitates" towards the design value of passengers (P=10) regardless of the initial value.

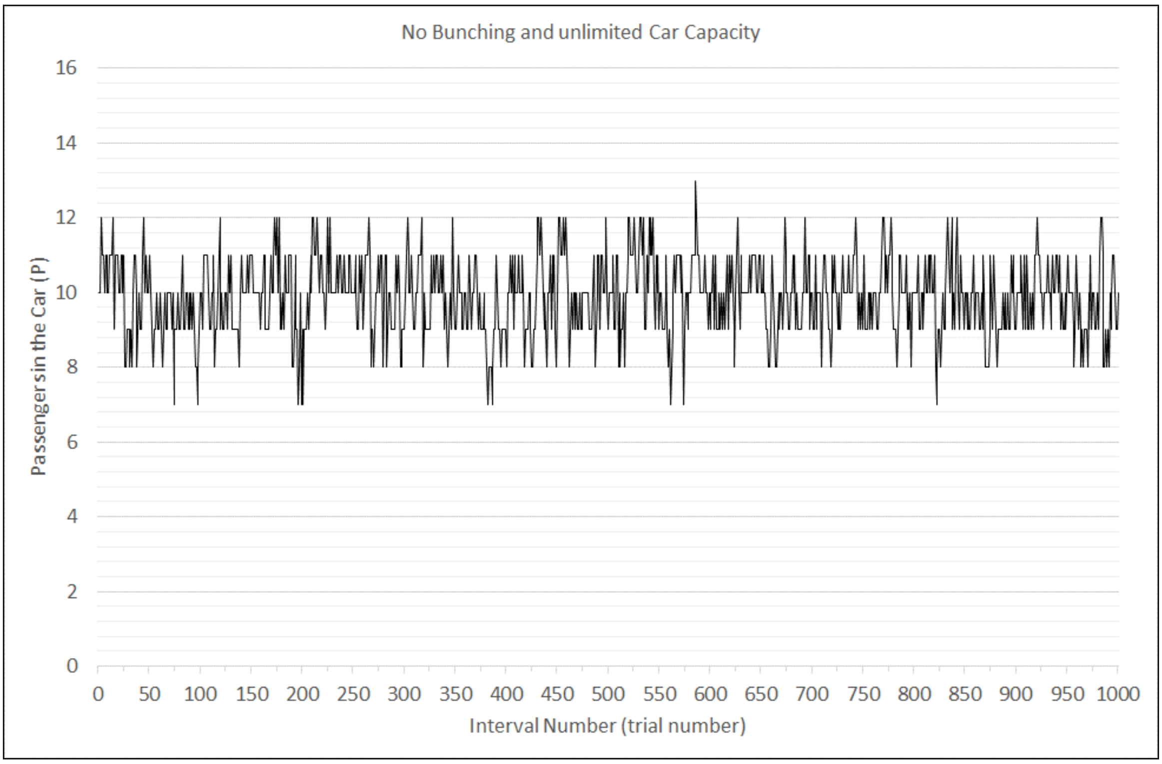

Figure 2: The number of passengers in the car in each trial without bunching and with unlimited car capacity.

The effect of bunching is then taken into consideration in the next figure (Figure 3). The "swings" in the number of passengers boarding is much larger than the case because this case considers both the value of the round trip time in the most recent trial as well as the difference between the values of the round trips for the latest two trials (which is a representation of the effects of bunching). Nevertheless, it is also remarkable to note that the average value of the passengers boarding the car is still equal to the design value of P=10 passengers.

The effect of bunching is taken into consideration as follows. The value of the previous round trip time is subtracted from the current value of the round-trip time. This is then divided by the number of elevators in the group in order to convert it from round-trip to interval. If the result is positive, it means that the current interval is longer than the previous interval and that there are more passengers arriving compared to the previous interval. If the result is negative, it means that fewer passengers would have arrived in the current interval compared to the previous interval. The difference between the two intervals is converted to units of passengers by multiplying the time difference by the arrival rate in units of passengers per second (i.e., λ). This provides the adjustment in the number of passengers. If positive the number is added to the number of passengers carried over to the next trial. If negative, it is subtracted from the number of passengers carried out to the next trial.

This algorithm recognizes the fact that the direct reason for bunching is the variability in the value of the round trip time in consecutive intervals.

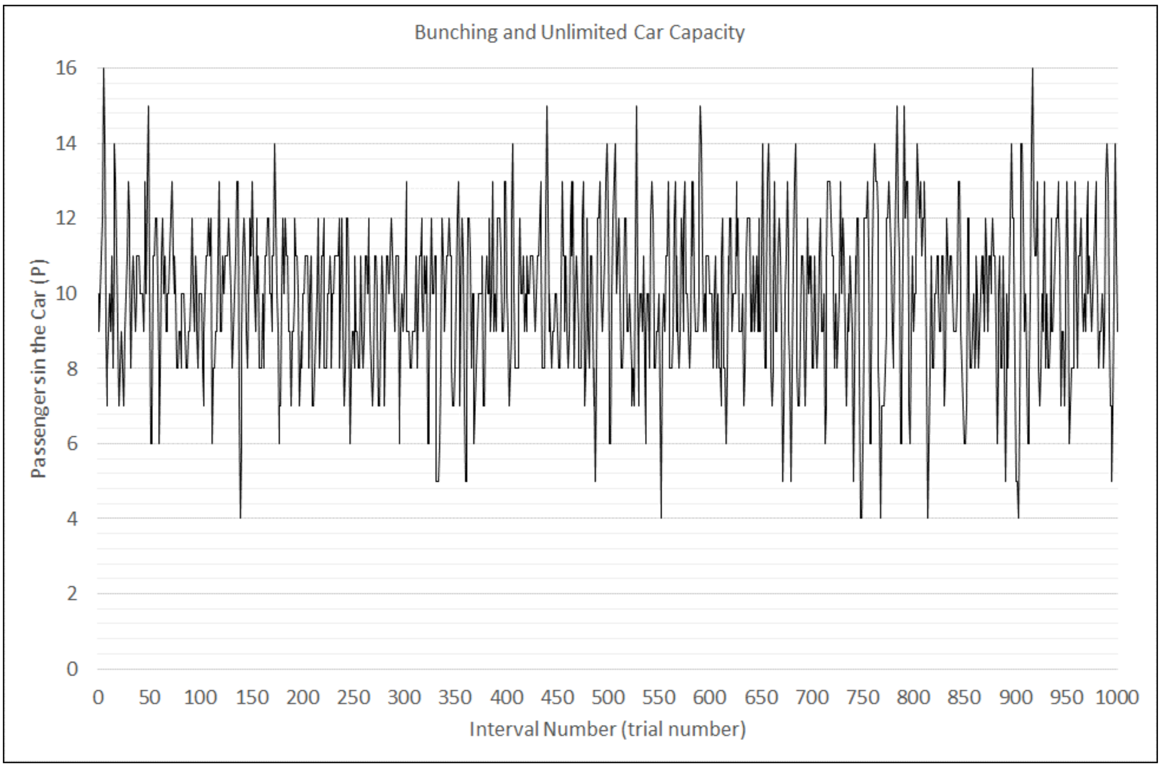

Figure 3: The number of passengers in the car in each trial with bunching and assuming unlimited car capacity.

It is worth noting that despite the variability on the value of the passengers board the car under the three setups (conventional MCS without interlinking; interlinked MCS without the effect of bunching; interlinked MCS with the effect of bunching) and the variability in the value of the round trip time under the three setups, the average value of the number of passengers boarding the elevator car is the same for the three setups as well as the average value of the round trip time. This is shown in the table below (Table 1).

It is worth noting that the original design of this building used 10 passengers (Pdes=10 passengers) and results in a design value for the round trip time of 133.5782333 s, and a design handling capacity of 12.477% of the population of the building, which has 900 residents.

Table 1: Average values of passengers boarding the elevator car and the average value of the round trip time under the conventional MCS and the two interlinked MCS algorithms.

Setup	MCS (constant car load)*	iLMCS unlimited car capacity without bunching	iLMCS unlimited car capacity with bunching
P	10.0	9.958	9.855
RTT (s)	133.57	133.02	131.6

* The design values for the building assuming 5 elevators in the group.

The most important conclusion from this section is the following: Despite the random variations in the value of the round trip time (caused by the passenger destination selections) and the random variations in the number of passengers boarding the elevator car in each round trip, these variations will not lead to a loss in the handling capacity of the elevator traffic system if the elevator car is assumed to have unlimited capacity. The average values of these two random variables will still converge to the same value assumed during the design process.

5. CONVERGENCE REGARDLESS OF THE INITIAL VALUE OF P

This section examines the convergence of the trials in the interlinked case. The question can be posed as follows: Do the future values of the round-trip time and the number of passengers in the car depend on the initial value used in the first trial? Or would these values converge to the correct value after enough trials?

In order to examine this point, the initial value of the number of passengers in the car was varied for the building under questions above and below the design value for the number of passengers in the car (which is P=10 in this case). Values of 1 passenger, 10 passengers and 20 passengers were used. The system was run for 100 successive interlined trials. This was done for both the bunching interlinked case and the non-bunching interlinked case.

It is interesting to note that in both cases and regardless of the initial value for P, the trials quickly converged to the expected value of P (i.e., P=10) after a small number of trials (Figure 4 and Figure 5).

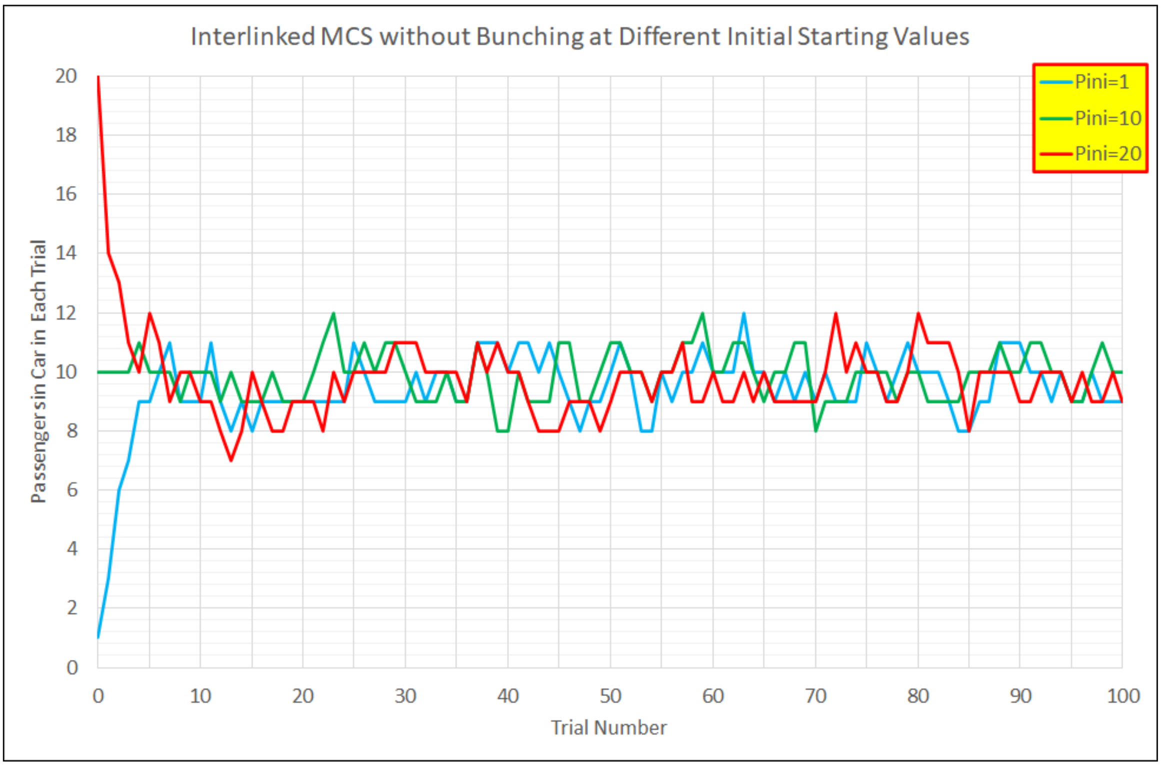

Figure 4: Convergence to the same value of P with different initial values not reflecting the effect of bunching.

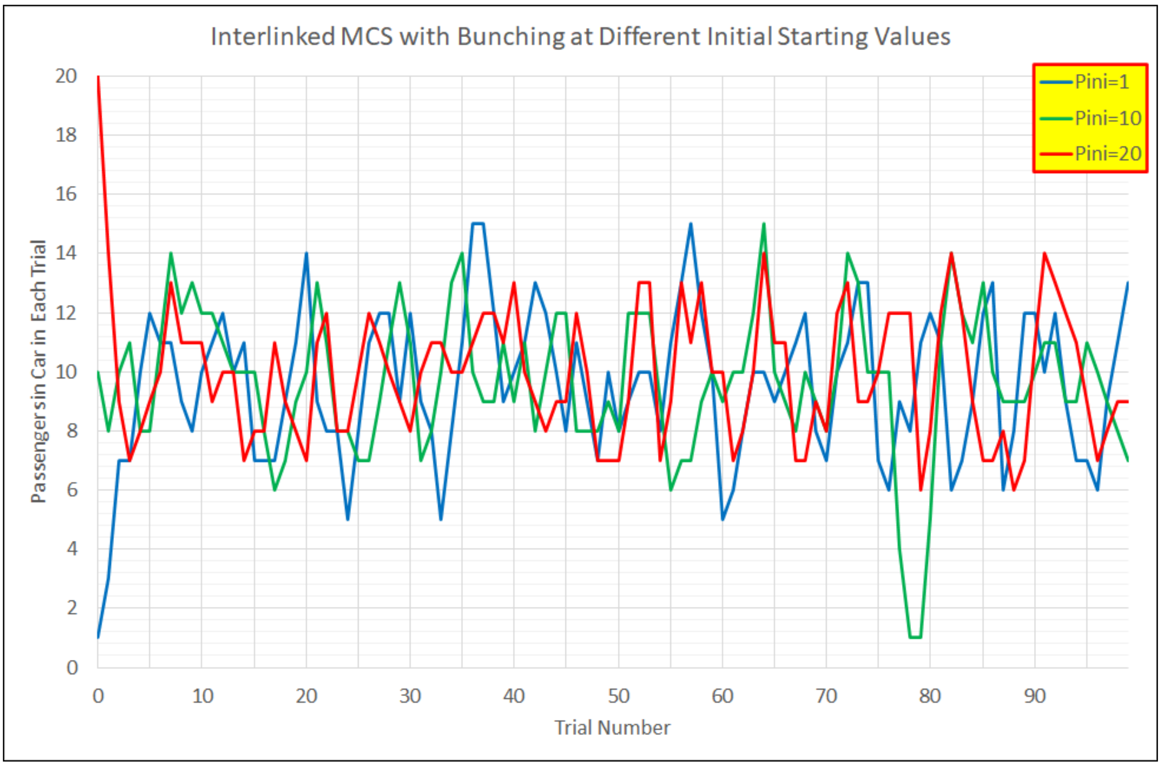

Figure 5: Convergence to the same value of P with different initial values including the effect of bunching.

This *self-correcting mechanism* is remarkably interesting in understanding the variation in the value of the round-trip-time around its mean value. However, it is important to note that this is only possible under the assumption of unlimited car capacity.

6. THE EVOLUTION OF THE QUEUE LENGTH BASED ON THE RATED OR ENLARGED CAR CAPACITY

In this section, it will be assumed that the car capacity is limited, in order to understand its effect on the system performance. Since the car capacity will be assumed to be restricted, a number of passengers might not be able to board the elevator car in each round trip and will be "carried-over" to the next trial. Thus it is possible for queues to start developing at the landing.

Thus, the passenger queue length at the landing(s) is examined. By definition, the inter-linked nature of this method of Monte Carlo simulation means that the number of passengers carried over from trial to the next is effectively the number of passengers left behind and "carried over" to the next trial.

To investigate the passenger queue length, 100 consecutive interlinked trials were run and the data gathered for the number of passengers in the queue collected. Each one of these series of 100 trials was then repeated 1000 times. These 1000 runs will be denoted as an "ensemble" a term that is borrowed from weather forecasting (in weather forecasting, a large number of forecasts are run each with a slightly different initial value, and the results are called an ensemble). By taking the average of all the runs in the ensemble, a smooth run of 100 consecutive interlinked trials is produced.

This results in good convergence and shows a repeatable result that is shown in Figure 6. Four graphs are shown, each one showing the number of passengers in the queue over 100 consecutive trials.

It is clear from the plot that when the car capacity is limited to the design number of passengers (Pdes), the number of passengers in the queue increases continuously. However, when the car capacity is increased by just one passenger, the queue length does not increase continuously, but stabilizes at a constant value.

The figures also show the effect of taking bunching into consideration, where this causes a slight increase in the length of the queue.

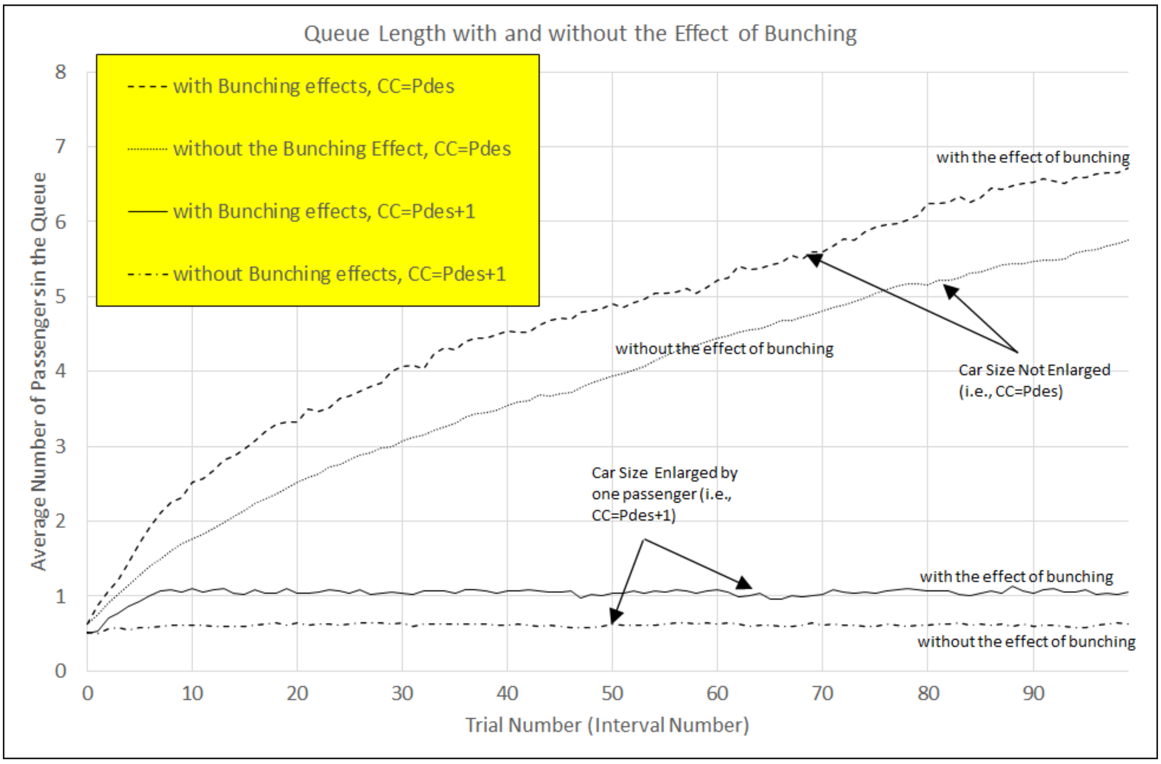

Figure 6: The passenger queue length with and without the effect of bunching.

This example clearly shows the importance of enlarging the elevator car capacity by a small amount in order to allow the queue length to stabilize. In this case, it was sufficient to increase it by one passenger, but further analysis is required on a number of different buildings in order to draw any firm conclusions about the required enlargement of the car capacity and its dependence on the parameters of the system being designed.

Another effect that can be observed when the results are further analysed is the actual achieved handling capacity. By processing the number of passengers in the car in each trial and the actual round-trip time, the actual handling capacity in each trial can be calculated. The average handling capacity is shown in Table 2 over all the 100 trials (averaged from the ensemble). It can be seen that bunching reduces the actual handling capacity below the design handling capacity. Limiting the elevator car size at the design number of passengers (Pdes) also causes a loss in the handling capacity from the design handling capacity of 12.477%.

Table 2: The calculated actual handling capacity under four setups.

Car capacity	Handling Capacity (HC%)	
	Without the effects of bunching	With the effects of bunching
CC=Pdes= 10	12.41%	12.39%
CC=Pdes+1=11	12.47%	12.46%

It is important to state that this building was based on the use of 10 passengers, a round trip time 133.5782333 s, and five elevators resulting in a design handling capacity of 12.477%. The building has 60 persons per floor over 15 floors, with a total population of 900 persons. The traffic was assumed to be incoming.

7. CONCLUSIONS

The Monte Carlo simulation has been successfully used to find the value of the elevator round trip time under general conditions, such as the multiple entrances, general traffic conditions, and rated speed not attained in one floor jump. It has also been used to find the value of the passenger transit time as well as the round-trip time under destination group control.

This paper has extended the use of the Monte Carlo simulation method in order to allow it to reflect the random nature of the passenger boarding the elevator in each round trip and the random variations in the value of the round trip. This has been done by inter-linking the consecutive trials by using the final value from one trial as the starting value for the next trial.

It has been shown that, despite the random variations in the value of the passengers boarding the car in each round and the random variation in the value of the round trip time, the average value of these remains equal to the design value of the elevator traffic system. it was also shown that as long as the car capacity is assumed to be unlimited, the handling capacity of the elevator traffic system is not reduced due to these random variations.

When the car capacity was limited to the design value of the passengers (Pdes), a slight reduction was observed in the handling capacity coupled with an increasing passenger queue at the landing. By increasing the car capacity by just one passenger, the handling capacity was restored, and the queue nearly disappeared. Although the required enlargement could be different for different systems and buildings, the general conclusion is that an increase in the car capacity from the design value is necessary in order to overcome the detrimental effects that could result from the random variations in the value of the number of passengers boarding the elevator car and the random variations in the value of the round trip time.

This paper has only addressed the effects of the randomness of the passenger destinations. Future papers will address the random effect of the passenger exact arrivals in time. Further research is also needed to identify the effects of enlarging the car capacity and how it impacts the queue length at the landing.

BIOGRAPHICAL NOTES

Lutfi Al-Sharif is currently Professor of Electrical Engineering at Al-Hussein Technical University in Amman/Jordan and jointly Professor of Building Transportation Systems at of the Department of Mechatronics Engineering, The University of Jordan. He received his Ph.D. in elevator traffic analysis in 1992 from the University of Manchester, U.K. He worked for 10 years for London Underground, London, United Kingdom in the area of elevators and escalators.

In 2002, he formed Al-Sharif VTC Ltd, a vertical transportation consultancy based in London, United Kingdom. He has over 30 papers published in peer reviewed journals the area of vertical transportation systems and is co-inventor of four patents and co-author of the 2nd edition of the Elevator Traffic Handbook.

He is also a visiting professor at the University of Northampton (UK), member of the management committee of the annual Symposium on Lift & Escalator Technologies and a consultant for Peters Research Ltd.

He is a passionate believer in making higher education simple and accessible for engineering students and has a You Tube channel on engineering that has more than 55 000 subscribers and around 8 million views. He has also been working as a member of the METHODS Erasmus+ Project that aims to improve teaching methods in higher education in Jordan and Palestine. He is also the author of the Mechatronics Engineering Module on Saylor.org.

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