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# A Review of Multi-Car Elevator System

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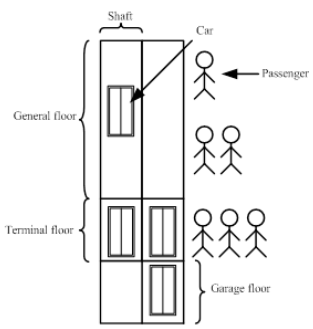
**Graphical abstract**




**Abstract**

This paper presents a review of a new generation of elevator system, the Multi-Car Elevator System. It is an elevator system which contains more than one elevator car in the elevator shaft. In the introduction, it explains why the Multi-Car Elevator System is a new trend elevator system based on its structural design, cost saving and efficiency in elevator system. Different types of Multi-Car Elevator System such as circulation or loop-type, non-circulation and bifurcate circulation are described in section 2. In section 3, researches on dispatch strategies, control strategies and avoidance of car collision strategies of Multi-Car Elevator System since 2002 are reviewed. In the discussion section, it reveals some drawbacks of the Multi-Car Elevator System in transport capability and the risk of car collision. There are recommendations to the future work as well.

*Keywords*: Avoidance of car collision; dispatch policy; multi-car elevator system



## 1.0 INTRODUCTION

The Multi-Car Elevator System (MCES) is an elevator system that has been developed in recent decades, which aims to increase the efficiency of elevator systems. The MCES is a big breakthrough to the traditional elevator system, known as Single-Car Elevator System (SCES), as the MCES no longer has any constraints to construct only one elevator car in one shaft. With no constraints, there can be more than one elevator car in a shaft, which enables the elevator system to plan the schedule of answering calls of passenger in a more effective way, thus greatly reduce the waiting time of passengers. In addition, with this special attribute of the MCES, it also saves much of the construction cost as 30% of the core-tube area of the elevators system is made up of shaft. To construct the MCES, a linear motor is chosen as it is one of enabling technologies that has been studied by many researchers [1-6] to cope with the problem of collisions between the elevator cars when there is no power supply and failure in the control system.

The first ever MCES was built in 2002 by the ThyssenKrupp Group [7]. It is known as a twin elevator which indicates that it has two elevator cars moving on one shaft. The types of MCES that exist in present are circulation or loop-type, non-circulation and bifurcate circulation. In the year 2002, researchers such as Sudo *et al.* [8] and Kita *et al.* [9] started to study MCES by proposing algorithms on the control strategies of MCES. Currently, there are many algorithms, dispatch strategies and control strategies that have been proposed. For example, zoning approach, search-based approaches, adaptive and learning approaches are the common approaches adopted in dispatch strategies in MCES. Besides, Genetic Algorithm (GA), Hybrid of Particle Swarm Optimization and Genetic Algorithm (PSO-GA), Multi-Agents System (MAS) and etc. are the algorithms that widely used for control strategies in MCES. The car collision is the critical problem in MCES, therefore many researches proposed strategies to avoid car collision. The strategies are limiting the direction of the elevator cars to travel only in the same direction, zoning approach, method of detection of car collision, mathematical analysis to get the probability and times equation of overstepping under different floor conditions in bifurcate MCES. Transport capability is one of the drawbacks in MCES and it is further discussed in section 4.

## 2.0 DESCRIPTION OF MULTI-CAR ELEVATOR SYSTEM

Overall, there are five basic elements in the structural design of MCES. The basic elements are floor, elevator car, elevator shaft, registration of destination floor and garage floor [10]. The descriptions of these elements are mentioned below.

**Floor-** It is a level of the building. Ground floor is the floor that passengers frequently pass through as it is the only point of exit or entry to the building, therefore it has the highest traffic demand. The ground floor is named "terminal floor", whereas the rest of the floors which experience normal traffic demand are named "general floor"

**Elevator car**- The transport that carry passengers to their corresponding destination floor. In MCES, there can be more than one elevator car in a shaft compared to SCESs.

**Elevator shaft**- It is the space or the pathway for the elevator car to move up and down.

**Registration of destination floor-** In order for the MCES to plan the schedule of answering the hall call, passengers are required to register the destination floor in the hall before they enter into the elevator car.

**Garage floor-** It is designed especially for the purpose to let the higher elevator cars to reach the terminal floor. If there are $m$ elevator cars, there must be $(m-1)$ garage floors [11].

The MCES is a complicated system that comprises multi-objective, non-linearity, uncertainty problem [12, 13]. In order to evaluate the performance of optimization, several terms are introduced, i.e., average waiting time of passengers (AWT), average travel time of passengers (ATT), rate of waiting longer time of passengers (RWLT), average crowding degree of passengers (ACD) and numbers of start-up and stop (NSS) [14-19]. AWT is the average time for the elevator car to reach the destination floor after a hall call button is pressed. ATT is the average time for a passenger to arrive at the desired floor after the passenger enters into elevator car. This is also the time taken from the AWT. RWLT is the percentage of the waiting time of a passenger over 1 minute after a hall call button is pressed. ACD is the percentage to measure the degree of comfort of a passenger which is determined by the number of passengers per elevator car. NSS is the number of start-ups and stops the elevator car made which is used to represent the energy consumption of elevator.

There are two major types of MCES, i.e., circulation or loop type MCES and non-circulation MCES. A circulation MCES comprises both vertical and horizontal movements whereas non-circulation MCES only possesses vertical movements. A circulation MCES can be further extended into another special type of circulation MCES, a bifurcate circulation MCES [20]. Figure 2.1–2.3 show the non-circulation MCES, circulation or loop type MCES, and bifurcate circulation MCES respectively.

In a non-circulation MCES, the cars can only move vertically and there must be no overlapping between the movements of the cars in order to avoid collisions. This type of MCES is commonly used as the construction design is not complicated compared to the other types of MCES.

For a circulation MCES, the cars are permitted to move horizontally at the bottom or at the top of the shafts so that the following car can answer a call of passengers by circulating the elevator system if the antecedence car is busy to transport passengers to the destination floor without turning back. The direction of both cars must in the same direction unless there is a problem of reversal or a deadlock arises [21]. Circulation property in this MCES leads to a reduction of waiting time for passengers and as well as the risk of collision between the car compared to non-circulation MCES. A circulation MCES is not suggested for being constructed due to its complicated design and high cost of construction.

In a bifurcate circulation MCES, other than circulating the elevator at the top of the shafts, the follow car can overstep the antecedence car at the designated planning floor. The overstepping can be done in two ways, i.e., normal overstep and abnormal overstep. In normal overstep, the antecedence car enters the lateral shaft so that the follow car can overstep it without moving into the lateral shaft. However, sometimes the antecedence car is unable to move into the lateral shaft first due to the situation where it needs to park at a designed planning main floor for unloading of passengers. When this occurs, an abnormal overstep needs to be performed by moving the follow car into the lateral shaft first and oversteps the antecedence car. Overstepping in bifurcate circulation MCES leads to a reduction of waiting time for passengers compared to a circulation MCES. However, due to the same reasons, complicated design and high cost plus the high risk of accidents during overstepping, causes it to become the least favorable type of elevator.

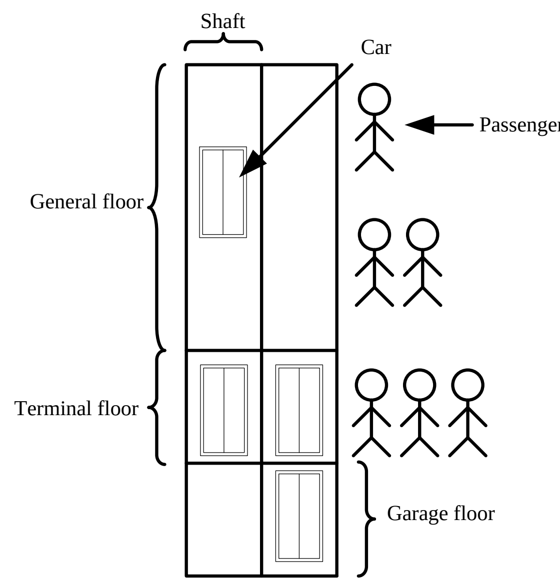



**Figure 2.1** Non-circulation MCES

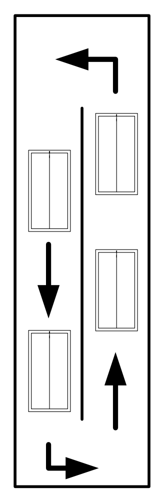


**Figure 2.2** Circulation or loop type MCES

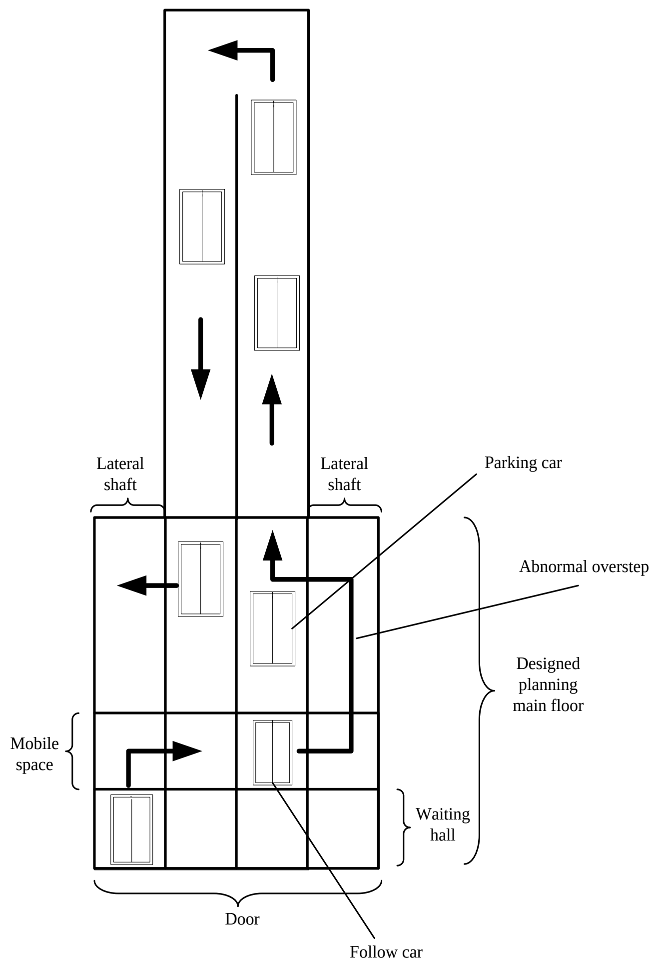



**Figure 2.3** Bifurcate circulation mces

## ■3.0 RESEARCH IN MULTI-CAR ELEVATOR SYSTEM

### 3.1 Dispatch Strategies in Multi-car Elevator System

An elevator system itself is a complicated problem system in which its decision needs to be made based on multi-input and multi-output [22]. Therefore, dispatching the elevator car to meet the optimized performance according to the different objective function is not an easy task. The dispatching policy of an elevator is one of the main concerns to be studied by many researchers. Zoning approaches are one of the earliest approaches in elevator dispatch systems [23-25]. It is an approach that divides the elevator shaft into different zones and assigns a particular elevator car to a particular zone to serve the passengers according to their traffic demand. Search-based approaches are also used in elevator dispatch systems to search for the best schedule to answer the call of passengers. Genetic algorithms in heuristic technique are one of the most common algorithms used in search-based approaches [26-27]. With the development of a fuzzy neural network, one of the artificial intelligence that uses adaptive and learning approaches, it helps elevator dispatching systems by knowing the traffic pattern of passengers at a specific time to serve the passenger accordingly by assigning an elevator car to the passenger [28-30]. Linguistic variables that exist in elevator system such as average waiting time, energy consumption, and traffic demand of floor can also be tackled by fuzzy logic using rule-based approaches [31-32]. Currently, the latest adaptive and learning approach is the multiple reinforcement learning agents which include rewards in a learning process [33-35]. Dispatch strategies in MCES are summarized in Table 3.1.

**Table 3.1** Summary of the dispatch strategies in MCES

| Dispatch strategies | Descriptions |
|---|---|
| Zoning approaches | - It is one of the earliest approaches in control strategies of MCES.<br>- It divides the elevator shaft into different zones and assigns a particular elevator car to a particular zone to serve the passengers according to their traffic demand |
| Search-based approaches | - It uses genetic algorithms which are found in heuristic technique to search for the best schedule to answer the call of passengers. |
| Adaptive and learning approaches | - It is found in fuzzy neural network, one of the artificial intelligence.<br>- It helps elevator dispatching systems by knowing the traffic pattern of passengers at a specific time to serve the passenger accordingly by assigning an elevator car to the passenger<br>- It solves linguistic variables by fuzzy logic using rule-based approaches<br>- The latest adaptive and learning approach is multiple reinforcement learning agents. It includes rewards in a learning process |

### 3.2 Control Strategies in Multi-car Elevator System

The control system in MCES has been extensively studied by many researchers and the first MCES twin elevator has adopted genetic algorithm to its elevator system due to its good overall optimization capability, simple algorithm, universal and robust [36]. Its performance is better than the minimum waiting time algorithm based on its evaluation of average waiting time, the incidence of long waiting time and the number of stops of car. In 2003, Takahashi *et al.* proposed a MCES control system using simulation-based optimization [44]. However, he found that this consumes a lot of computational time. Hence, he adopted two devices to improve the speed of computation, i.e. personal computer system for the evaluation of fitness values in parallel and genetic algorithm explicitly considering fitness functions involving noise. This approach has increased the optimization performance for the controller. The evaluation based on the results given is executed without exceeding the computation time and control pattern of MCES can be studied in detail. In 2006, Ikeda *et al.* proposed another algorithm for simulation–based approach, i.e. genetic algorithm with vector-vector style exemplar-based policy representation [45]. The advantage of this approach is the decision-making framework becomes more flexible and enables more certainty for the elevator states in MCES. Subsequently, Ikeda *et al.* modified his algorithm by adopting multi–objective function to his previous work [46]. The modification has shown better improvements in controlling MCES.

In 2007, Markon *et al.* proposed a control system of MCES using a consecutively running real-time genetic algorithm method

[47]. The result of this method surpassed all the existing heuristic methods. In 2013, Minegishi *et al.* proposed an algorithm called Hybrid solving Method for MCES (HMM) using a Constraint Program (CP) and Mixed Integer Program (MIP) [49]. This hybrid method shows superiority over the Integer Program (IP) and a Mixed Integer Program (MIP) technique. In 2014, Liu *et al*. proposed a hybrid of Particle Swarm Optimization and Genetic Algorithm (PSO-GA) method [48] in circulation MCES. The result showed that the convergence performance and optimization accuracy is much better than genetic algorithm

In addition, Multi-Agents System (MAS), one of the adaptive and learning approaches is also implemented in control systems of MCES. In 2013, Ikuta *et al.* adopted the MAS to inspect and select the best method among the combination of the four strategies, i.e. difference strategy, transportation strategy, zone strategy and passenger strategy to make the performance of the method better [50]. The results showed better performances compared to only single strategy applied. In 2014, Ahmad *et al.* also adopted MAS and proposed a hybrid model containing the colour-timed transition Petri net (CTTPN) [51]. This method was able to find the cooperation between the elevators and solved the bunching problem. Bunching is a traffic pattern formed when a number of elevators move around a building together, instead of being separated in the building. The development of control strategies in MCES from 2002 to 2014 is summarized in Table 3.2

**Table 3.2** Summary of the development of control strategies in MCES from 2002 to 2014

| Year | Control strategies | Descriptions |
|---|---|---|
| 2002 | Genetic algorithm | - It is adopted in twin elevator<br>- Its performance is better than the minimum waiting time algorithm based on its evaluation of average waiting time, the incidence of long waiting time and the number of stops of car. |
| 2003 | Simulation-based optimization | - It has drawback of consuming a lot of computational time<br>- It is modified by adopting two devices to improve the speed of computation, i.e. personal computer system for the evaluation of fitness values in parallel and genetic algorithm explicitly considering fitness functions involving noise<br>- The modification improves the computation time and the control pattern of MCES can be studied in detail |
| 2006 | Genetic algorithm with vector-vector style exemplar-based policy representation in simulation-based optimization | - It improves simulation-based optimization<br>- It has advantage of flexibility in decision-making framework and enables more certainty for the elevator states in MCES<br>- It is modified by adopting multi–objective function to his previous work |
| 2007 | Consecutively running real-time genetic algorithm | - It surpasses all the existing heuristic methods |
| 2013 | Hybrid solving Method for MCES (HMM) using a Constraint Program (CP) and Mixed Integer Program (MIP) | - It shows superiority over the Integer Program (IP) and a Mixed Integer Program (MIP) technique |
| 2013 | Multi-Agents System (MAS) | - It is one of the adaptive and learning approaches<br>- It inspect and select the best method among the combination of the four strategies, i.e. difference strategy, transportation strategy, zone strategy and passenger strategy<br>- It has better performances compared to only single strategy applied |
| 2014 | Hybrid model containing the colour-timed transition Petri net (CTTPN) in MAS | - It able to find the cooperation between the elevators and solved the bunching problem |
| 2014 | Hybrid of Particle Swarm Optimization and Genetic Algorithm (PSO-GA) method | - Its convergence performance and optimization accuracy is much better than genetic algorithm |

### 3.3 Collision Avoidance Strategies of Elevator Car in Multi-Car Elevator System

When a contractor wants to use the new generation of elevator system, i.e., MCES, the problem of the elevator system no longer lies on the dispatch policy and control strategies, but the problems include the collision avoidance of elevator cars, deadlock, livelock and reversal. For the sake of collision avoidance between the elevator cars, the twin elevator, the first MCES (2002) which has two elevator cars in a shaft, has adopted the approach of limiting the direction of the elevator cars to travel only in the same direction [36]. This restriction causes the performance of the optimization of the elevator system to become extremely inefficient. Consequently, zoning approach is adopted and it is further improved by researcher Valdivielso *et al.* by considering the avoidance of elevator car collision, optimization of floor-call allocation and car selection to answer hall calls [37]. In favour of avoiding the car collision, parking strategies of the elevator car have been proposed by Valdivielso *et al.* This helps to balance the distribution of elevator cars that are prepared to answer the hall call. Scheduled completion time algorithms are proposed by Valdivielso *et al* as well to optimize the car selection for the floor-call allocation. The zoning approach that included inter-floor and down peak traffic patterns showed better performances than the previous zoning algorithm. In 2013, Ishihara *et al.* modified the zoning approach by proposing a multi-car elevator control using dynamic zoning. In this method, the size of the zone is not fixed, it varies in accordance to the assignment of hall calls or the movement of the elevator car to transport passengers to the destined floor. By adopting the dynamic zoning approach, the movement of the elevator car is no longer restricted compared to the previous zoning approach and yet improved the efficiency of the elevator dispatching system [38].

Besides using zoning approach to tackle the problem of car collision, there are specific algorithms proposed by many researchers to solve the problem [39]. In 2009, Tanaka *et al.* proposed an algorithm of car collision avoidance and introduced a method of detection of car collision [40]. In the method of detecting the car collision, all the floors are divided into half and by checking whether the cars share the same half floor, the possible car collision can be detected. Although this algorithm has successfully improved the efficiency of the transport capability, the problems of reversal and livelock are raised due to the constraint of the algorithm i.e., instead of changing the order of the service, evacuation travel is applied as the order of service cannot be changed once it is given. Reversal is the unwanted travelling of the elevator car in the opposite direction to the desired floor of the passengers. Livelock is a state where the elevator car is not able to load or unload passengers [41]. These problems are later solved by Tanaka *et al.* in which he modifies the algorithm by changing the objective function of the algorithm i.e., the car is allowed to pass through the source floor of a call in the schedule and the service for that call is postponed until there is no passenger in the car and allow at least one car approach to the next scheduled floor [42]. By modifying this algorithm, the elevator is able to achieve reversal and livelock free operations.

Researchers have also studied car collision avoidance in circulation MCES and Liu *et al.* is one of the researchers that studied bifurcate MCES [43]. In bifurcate MCES, normal overstep is always prior and abnormal overstep should always be avoided. For this purpose, Liu *et al.* uses mathematical analysis to get the probability and times equation of overstepping under different floor conditions. His mathematical analysis has contributed to avoiding abnormal overstep in bifurcate MCES. The car collision avoidance strategies in MCES are summarized in Table 3.3

**Table 3.3** Summary of the car collision avoidance strategies in MCES

| Car avoidance strategies | Descriptions |
|---|---|
| Limiting the direction of the elevator cars to travel only in the same direction | - The restriction causes the performance of the optimization of the elevator system to become extremely inefficient |
| Zoning approach | - It considers the avoidance of elevator car collision, optimization of floor-call allocation and car selection to answer hall calls<br>- Scheduled completion time algorithms are proposed to optimize the car selection for the floor-call allocation<br>- The zoning approach that included inter-floor and down peak traffic patterns showed better performances than the previous zoning algorithm<br>- It is modified into dynamic zoning approach in which the size of the zone is not fixed, it varies in accordance to the assignment of hall calls or the movement of the elevator car to transport passengers to the destined floor |
| The algorithm of car collision avoidance and a method of detection of car collision | - All the floors are divided into half and by checking whether the cars share the same half floor, the possible car collision can be detected<br>- The problems of reversal and livelock are raised due to the constraint of the algorithm<br>- The algorithm is modified by changing the objective function of the algorithm to achieve reversal and livelock free operations |
| Mathematical analysis to get the probability and times equation of overstepping under different floor conditions | - It contributes to avoiding abnormal overstep in bifurcate MCES |

## 4.0 DISCUSSION

Dispatch system in MCES is a complicated system compared to SCES because it involves a car controller, group controller and shaft controller. The car controller is responsible for planning the schedule of the calls, the group controller is responsible for call assignments and the shaft controller is responsible for car collision avoidance [52]. Approaches such as zoning, parking strategy, avoidance of car collision algorithm, genetic algorithm, PSO-GA, MAS etc. are adopted for the avoidance of car collision and optimizing the performance of AWT, ATT, RWLT, ACD and NSS in MCES.

Although MCES has advantages of saving construction cost and minimizes the waiting time for passengers, the risk of accidences of the elevators is still high because the possibility of the cars colliding cannot be neglected. Circulation MCES are one of the approaches that can minimize the problem of car collision, however its complicated design and lack of research causes it to become impractical to construct. A MCES still cannot solve the problem of transport capability unlike the Double-Deck Elevator Systems (DDES), an elevator system which contains an elevator car with two cages i.e., a lower cage and an upper cage merged together [53]. This is especially important in high-rise buildings for transporting large quantities of passengers during peak hours. The limited space in elevator cars in MCES means that the cars are unable to transport all the passengers at once, which causes passengers need to wait for the next elevator car and leads to a long waiting time. In the future, elevator system research can focus on designing a simpler MCES and figure out a way to support more passengers at one time.

## 5.0 CONCLUSIONS

MCES is a new trend in elevator system due to its low cost of construction and is able to minimize the waiting time of passengers. However, multiple cars in one shaft carries a high risk of car collision. Zoning approach, parking strategy, avoidance of car collision algorithm and circulation MCES are some of the solutions to it. In order to meet the optimization performance in reducing waiting time of passengers and energy consumption, approaches such as genetic algorithm, MCA, PSO-GA etc. are broadly used. Due to the problem of limited space for transporting passengers in MCES, alternative approaches need to be figured out to overcome this.

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