Elevator System with Multiple Cars in One Hoistway

by Masami Sakita

Learning Objectives

After reading this article, you should have learned that:

◆ Having an elevator system with multiple cars in the same hoistway is an old idea, but except for one experimental use in the very early days, it has not been used in the real world for a long time.

◆ Elevator systems with multiple cars in the same hoistway in large office buildings are used to increase lifting capacity.

◆ Elevator systems with multiple cars in the same hoistway in residential buildings may be used for each car to provide a different type of service.

◆ Elevator systems with multiple cars in the same hoistway must be equipped with one or more collision-prevention system(s) to ensure safe operation.

◆ The round-trip time is the key parameter in an elevator system's design.

◆ The time-space diagram is an important tool used in the design and analysis of transportation systems, including the elevator system.

◆ Normalized capacity and normalized net capacity are key indicators that express the elevator system efficiency.

◆ Elevator shafts may be minimized (or optimized) when each car in the shaft stops at few floors.

◆ It is important to have enough spare shafts that can be used when elevator shafts fail.

◆ Computing operational parameters using the deterministic method (instead of the probabilistic method) works fine when one deals with a system that has few stops in the morning peak period.

Value: 2 contact hours (0.2 CEU)

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This article discusses a system design methodology of the multiple-car elevator system that can be used in the planning stage of an office building. The system design objective is to minimize the required floor space for the elevator system and, possibly, the total travel time, while keeping wait times at the main lobby within an acceptable level. This article discusses key operation methods and shaft designs, estimation of floor space used for elevator shafts and waiting areas, and selection of car size and the optimum number of floors to be served by an elevator car.

Introduction and Background

Since Sprague's Dual Elevator System (which became operational in a 20-story Pittsburgh building in 1931) was taken out of service, no elevator systems that had more than one elevator car in one shaft had been operational anywhere in the world[1] until 2003, when ThyssenKrupp Elevator AG announced its TWIN elevator system.[2] The multiple-car elevator system on which design methodology is discussed in this article features multiple cars in one hoistway, as shown in Figure 1.[3, 4 & 5]

In the multiple-car elevator system, as many as three cars (or three tandem
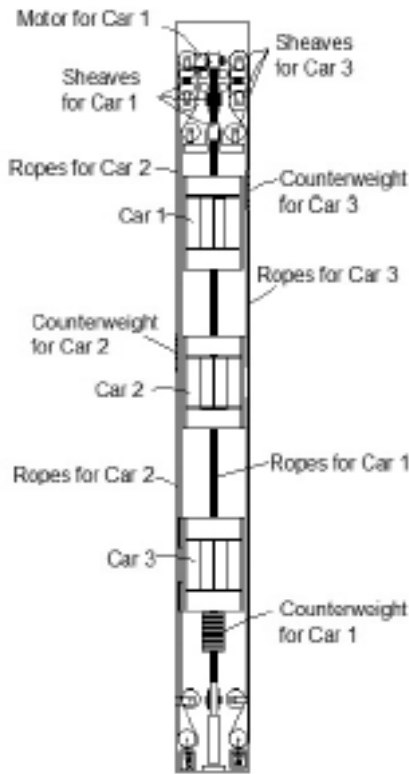
Figure 1: The multiple-car elevator system

units of permanently coupled cars) can be installed in the same shaft, in which each car (or each tandem unit) is hoisted by its own hoist cables so that each car (or tandem unit) operates independently. The elevator cars in the shaft operate like self-driven railroad passenger cars on a short stretch of a railroad track, with the constraint that all elevator cars are allowed to travel only in the same direction at any given time.

To ensure that the elevator cars in the same shaft will not have collisions under any circumstance, all cars in the same shaft are mechanically interlocked by bidirectional, one-way clutch systems for both up and down movements. The one-way clutch allows all elevator cars to move only in one direction at a time. Any neighboring cars may be mechanically protected from colliding with each other by the device attached to the elevator car that grabs the adjacent car's ropes. Any two neighboring

cars may be mechanically coupled by the same device at any time, at any distance between them. Each elevator car is protected by redundant independent brake systems. The system is controlled by three layers of computer systems, (each equipped with software) –one for controlling passenger flow for the entire system, one for controlling each shaft and one for controlling each elevator car.

The multiple-car elevator system includes various combinations of operation methods and shaft design, and the size of the motor ranges from small (in which three motors may be installed in one floor shaft of a short building) to large (in which one motor occupies one floor shaft of a tall building) as required. Thus, building types in which the multiple-car elevator system is used can vary from short and small to super tall and large.

The multiple-car elevator system may be used in two distinctly different ways. One way is to take advantage of the enormous capacity of the elevator shaft (thus being able to reduce necessary floor space). The other way is to provide different types of service. The former applies to the office building as discussed in this article, and the latter applies to a residential building in which, for example, the top car in the shaft serves the top few floors for premium customers, the middle car serves the rest of the floors, and the bottom car carries the cargo or the building maintenance crew.[6 & 7]

The following sections describe various operation methods and shaft designs of the multiple-car elevator system; the method by which to choose the best operation method, and elevator car size and zone size; and numerical examples to demonstrate how the design methodology may be used in the elevator shaft design. The process described in these sections is intended to be used in the planning stage of an office building

that is able to take advantage of the high-capacity characteristics of the multiple-car elevator system. The analysis process is also applicable to the conventional elevator system.

Shaft Design and Operation Methods in Multiple-Car Elevator Systems

The operational characteristics of multiple-car elevator systems are defined by five attributes. These are expressed as a string of five letters, each separated by a slash on either side – $u/c/m/n/f$. The first letter, u, indicates the type of operational unit: $u = 1$ is a single-car operation system, $u = 2$ is a two-car tandem operation system (in which two cars may be temporarily coupled for the duration of operation or permanently coupled, as in the double-decker unit), and $u = 4$, a four-car tandem operation system. The second letter, c, indicates the number of floors the elevator cars skip at every movement up or down within the zone: $c = 0$ indicates that the car serves only one floor in the one-floor zone, $c = 1$ indicates that the car serves every floor in the multiple-floor zone, $c = 2$ indicates that the car stops at either every odd or even floor in the zone, and $c = 4$ indicates that the car stops at every fourth floor in the zone. The third letter, m, indicates the number of cars in a shaft. The fourth letter, n, indicates the number of floors in the zone. The fifth letter, f, indicates the number of floors at the main (ground-floor) lobby.

In describing the system's characteristics, the known quantities of these attributes are expressed as numbers, and the undefined ones are expressed as letters. For example, a conventional elevator system with an n-floor zone that may be considered a special case ($m = 1$) of the multiple-car elevator system, is defined as $1/1/1/n/1$. Its operational unit is a single car, its operation method is the basic method, it has

one car in a shaft, it has an *n*-floor zone, and its main floor consists of one floor. Some of the most promising operation methods that involve the main-floor lobby design in terms of the number of floors are briefly described below.

Basic Operation (1/1/m/n/1)

In the basic operation method, all cars in the shaft group serve all floors in the zone (Figure 2).

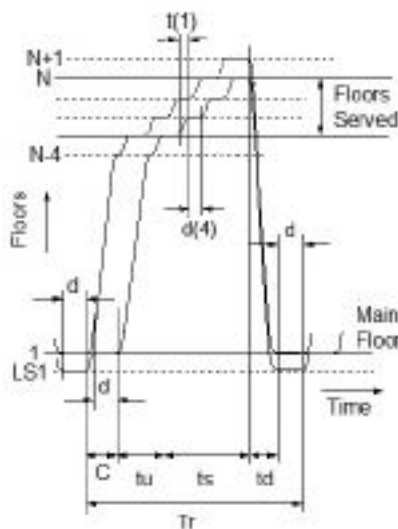### Single-Car, Odd/Even, Skip/Stop Operation (1/2/m/n/1)

In the single-car, odd/even, skip/stop operation method, each car in the shaft group is assigned to serve either even-numbered floors or odd-numbered floors, but the cars are not coupled when operated. The main floor is a single floor, and the odd/even pair of cars are time separated (Figure 3).

Two-Car Tandem, Odd/Even Operation (2/2/m/n/2)

In this method, every pair of cars is coupled together and forms a tandem unit that travels up and down in unison with the upper car serving the even-numbered floors and the lower car serving the odd-numbered floors. The main lobby of the building will consist of two floors – upper main floor for the upper car and lower main floor for the lower car.
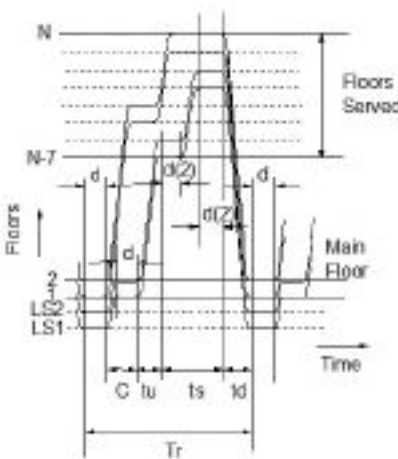
Two-Car Tandem, Skip/Stop Operation (2/m/m/n/2)

In this operation method, every pair of cars is also coupled together and forms a tandem unit that moves up and down in unison, with the upper car serving the even-numbered floors, and the lower car the odd-numbered floors. However, each pair of cars is assigned to serve not every pair of floor units, but every other pair of floors – every car serves every *m*th floor. The main floors will consist of two floors: the upper floor for the upper car and the lower floor for the lower car. For this method to be effective, *n* must be a multiple of *m* (Figure 4).

Figure 2: A sample time-space diagram for basic operation when $m = 2$ and $n = 4$, and its round-trip time equation (1/1/2/4/1).

$$Tr = \text{Round-trip time} = d + 3C + tu + ts + td$$
$$= d + 4d(4) + 4t(1) + t(N - 5) + t(N)$$

Figure 3: A sample time-space diagram for odd/even operation when $m = 2$ and $n = 4$, and its round-trip time equation (1/2/2/4/1).

$$Tr = \text{Round-trip time} = d + C + tu + ts + td$$
$$= 2d + t(1) + 2d(2) + t(2) + t(N - 4) + t(N-1)$$

Figure 4: A sample time-space diagram for two-car tandem skip/stop operation when $m = 4$ and $n = 8$, and its round-trip time equation (2/4/4/8/2).
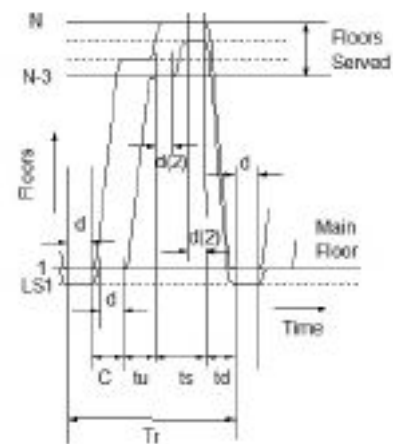
$$Tr = \text{Round-trip time} = d + C + tu + ts + td$$
$$= 2d + 2d(2) + t(2) + t(4) + t(N - 8) + t(N - 2)$$

Figure 5: A sample time-space diagram for two-car tandem express operation when $m = 4$ and $n = 4$, and its round-trip time equation (2/0/4/4/2).

$$Tr = \text{Round-trip time} = d + C + tu + ts + td$$
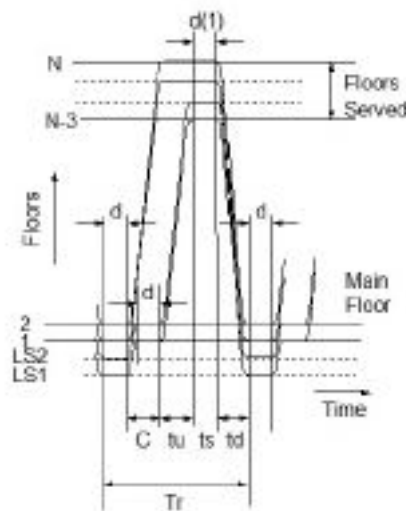$$= 2d + d(1) + t(2) + t(N - 4) + t(N - 2)$$

Two-Car Tandem Express Operation (2/0/m/n/2)

In this operation method, just as in standard two-car tandem operation, every pair of cars is coupled together to form a tandem unit and moves up and down in unison, with the upper car serving the even-numbered floors, and the lower car serving the odd-numbered floors. However, this is a special case in which each car serves only one floor – the tandem units travel directly to the destination pairs of floors. The main floors will consist of two floors: the upper floor for the upper car and the lower floor for the lower car. This operation is most effective if $m = n$ (Figure 5).

Normalized Capacity and Normalized Net Capacity of a Shaft

The normalized capacity of a shaft is the maximum number of passengers

that can be carried in a unit time period per unit area of the shaft, which is expressed as the product of the number of trips made by the elevator cars in the shaft in a unit time and the number of passengers carried in a unit shaft area in one trip. The normalized capacity of the shaft is expressed as:

$$C_n = 3600mN_p/(T_rA) \quad \text{(Equation 1)}$$

where
C_n = Normalized capacity (passengers per hour/sq. ft.)
m = Number of elevator cars in the same shaft (cars)
N_p = Nominal capacity of car (passengers)
T_r = Round-trip time (seconds)
A = Shaft space (sq. ft.)

The normalized net capacity of a shaft reflects the maximum number of passengers that can be carried by the system per unit shaft space, including extra shaft floors at the top and bottom of the shaft, per unit time. The normalized net capacity of the shaft is expressed as:

$$P_n = 3600mN_pN_f/(T_rAn)$$
$$= C_nN_f/n \quad \text{(Equation 2)}$$

where
P_n = Normalized net capacity (passengers per hour/sq. ft.)
N_f = Number of serviceable floors
n = Total number of floors used in the shaft

The normalized capacity and the normalized net capacity for unidentified shaft height of selected elevator systems that use hypothetical 13- or 26-passenger cars are shown in Tables 1 and 2, respectively. The numerical values in each capacity in Table 1 and each net capacity in Table 2 reflect the number of passengers carried at a time in the unit area of the shaft. The four cars per shaft system in Tables 1 and 2 (see "/4/" in the operation method parameter) uses four cars comprising two permanently coupled, two-car units in a shaft.

To estimate how well each elevator operation method (and elevator system design) will compare against the conventional elevator system, we computed the normalized capacity and the normalized net capacity divided by

Normalized Shaft Capacity (X 10³ passengers per hour/sq. ft.)

Operation Method	13-Passenger Car	26-Passenger Car
(1/1/1/n/1)	11.14/T_r*	12.91/T_r
(u/c/2/n/f)	20.17/T_r	23.91/T_r
(2/c/4/n/2)	40.34/T_r	47.82/T_r

*Round-trip time (seconds)

Table 1

Normalized Net Shaft Capacity (X 10³ passengers per hour/sq. ft.)

Operation Method	13-Passenger Car	26-Passenger Car
(1/1/1/n/1)	11.14 (N_f/n)/T_r*	12.91 (N_f/n)/T_r
(u/c/2/n/f)	20.17 (N_f/n)/T_r	23.91 (N_f/n)/T_r
(2/-/4/n/2)	40.34 (N_f/n)/T_r	47.82 (N_f/n)/T_r

*Round-trip time (seconds)

Table 2

the normalized capacity of the conventional system for a shaft height of 16 stories and higher. These values are called relative capacity and relative net capacity of the multiple-car elevator system, relative to that of the conventional system. The relative capacity and relative net capacity of some key operational methods to the conventional system for different shaft heights are shown in Figures 6 and 7, respectively. Figure 7 shows that the higher the shaft height, the higher the relative net capacity. Figure 7 shows that the two-car tandem system has close to twice the net capacity, and the four-car-per-shaft systems have about four times higher net capacity than the conventional elevator system per unit shaft area, including the extra shaft floors, implying that the extra shaft space used in the multiple-car elevator system is not having much adverse effect.

Round-Trip Time

The round-trip time is probably the most important parameter used in the elevator-system design process. The round-trip time (T_r) consists of dwell time at the main floor, upward travel time, service time at each floor, travel times between floors and downward travel time. Of
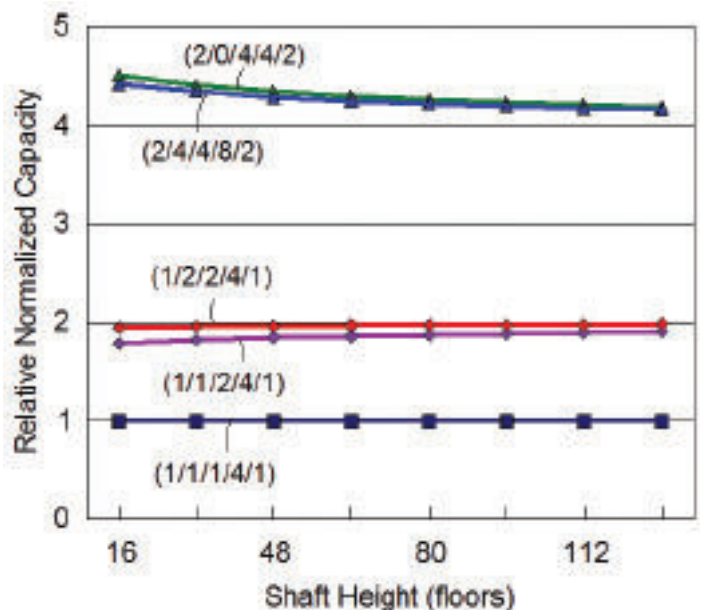

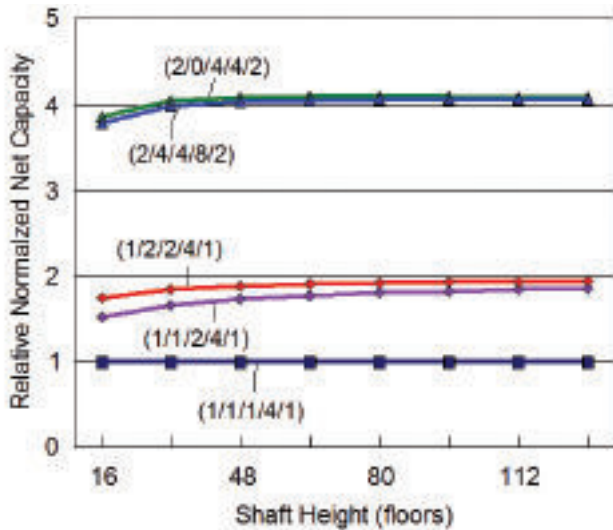Figure 6: Normalized capacity comparison

Figure 7: Normalized net capacity comparison

these, the dwell time at the main floor and the service time in the zone (service time at each floor and travel times between floors in the zone) are the only factors that vary depending on the operation method used for a given shaft height and zone size, and the upward and downward travel times remain the same in all operation methods. Thus, the operation method that minimizes the dwell plus service time in the zone will minimize the round-trip time.

The round-trip time of an elevator car in the morning peak period, $T_r(n_f)$, for a car in the shaft that serves the top n_f floors of an unidentified height shaft is obtained from:

$$T_r(n_f) = T_{dw}(n_f) + T_u(n_f) + T_s(n_f) + T_d \qquad \text{(Equation 3)}$$

where
n_f = The number of floors served by a car in the zone
$T_{dw}(n_f)$ = The dwell time at the main floor (seconds)
$T_u(n_f)$ = The upward travel time to the lowest served floor (seconds)
$T_s(n_f)$ = The service time in the zone (seconds)
T_d = The travel time from the top floor to the main floor (seconds)

For a shaft of a given height N, the round-trip time is determined by the number of passengers in the car and the number of stops the car makes in the trip. For example, in the conventional system, the round-trip time of a car that serves the top n_f floors of an N-story shaft in the morning peak period is estimated from the following equation:

$$T_r(N, n_f) = (5 + n_p) + t(N - n_f) +$$
$$(n_f - 1)t(1) + n_f(5 + n_p/n_f) + t(N - 1) \qquad \text{(Equation 4)}$$

where $t(i = 1)$ is the time required to travel ($i = 1$) floor(s) from start to stop, and n_p is the number of passengers in a car. (It is assumed that $n_p = 0.8N_p$.) When the shaft height N needs not to be specifically identified, $T_r(N, n_f)$ is written as $T_r(n_f)$ to avoid unwieldiness throughout this article.

In Equation 4, the first term shows the dwell time at the main floor, the second term shows the upward travel time, the third term shows the travel times between the served floors, the fourth term shows the total dwell time at the served floors, and the fifth term shows the downward travel time. The third and fourth terms together make up the service time.

Assuming that the car travels at the maximum speed of 26.2 fps (8 mps), and the operational acceleration and deceleration rates are both 1.64 fps² (0.5 mps²), and a floor in a building is 13.1 ft. (4 m) high, the trip time for traveling n floors from start to stop, $t(n)$, is expressed as:

$$t(n) = 0.5n + 14.6 \qquad \text{for } n > 16 \qquad \text{(Equation 5)}$$

$$= 2\sqrt{8n} \qquad \text{for } n \leq 15 \qquad \text{(Equation 6)}$$

The acceleration/deceleration rate of 1.64 fps² (0.5 mps²) is used for travel of all types. The dwell time at each floor is assumed to be expressed as:

$$d(n_f) = 5 + n_p/n_f \qquad \text{for single-car operation} \qquad \text{(Equation 7)}$$

$$= 7 + n_p/n_f \qquad \text{for tandem operation} \qquad \text{(Equation 8)}$$

where n_f is the number of stops (or served floors) in one trip (in express operation, $n_f = 1$), and n_p is the number of passengers carried in one trip. The dwell time at the main floor is assumed to be the same as that for the dwell time at $n_f = 1$.

The travel time between the floors served in a zone (jump time) is computed from Equation 6 to be $t(1) = 5.7$ seconds, $t(2) = 8.0$ seconds, and $t(4) = 11.3$ seconds. The round-trip time is estimated using the travel and dwell times as defined above. The marginal time for serving one extra floor, which is crucially important in determining the optimum operation strategy, may be estimated at 10.2 seconds in the basic operation and single-car, two-layer operation (not presented in this article); 14 seconds in the tandem odde/even, two-floor, skip/stop operation; and 16.3 seconds in the tandem four-floor, skip/stop operation, all for the single-shaft system.

In order to compute the number of passengers in a car, n_p, at the time of starting from the main floor, we introduce

Continued

the concept of the required dispatch interval, $T_{dr}(n_f)$, and the operational dispatch interval, $T_{do}(n_f)$. The required dispatch interval, $T_{dr}(n_f)$, is the "required" time interval between the two consecutive elevator cars' arrivals at the main floor to handle the morning peak 5-minute passenger demand and is determined from:

$$T_{dr}(n_f) = 300 \, \alpha N_p / (D_p n_f) \qquad \text{(Equation 9)}$$

where

$T_{dr}(n_f)$ = Required dispatch interval (seconds)
α = Average load factor (0.8 is used)
N_p = Nominal passenger capacity of a car (number of passengers)
D_p = Passenger demand (number of passengers per 5 minutes per floor)
n_f = Number of floors served by a car

The operational dispatch interval is the average of dispatch intervals at the main floor computed from the round-trip time. In both cases, it is assumed that each car will be operated on an average 100α percent full. ($\alpha = 0.8$ is used.) The operational dispatch interval, $T_{do}(n_f)$, is obtained from a relationship, such that

$$T_{do}(n_f) = T_r(n_f) / [N_s(n = n_u n_f)] \qquad \text{(Equation 10)}$$

where

$T_r(n_f)$ = Round-trip time of a car in the shaft that serves top n_f floors in the N-story shaft group (seconds)
$N_s(n = n_u n_f)$ = Number of N-story shafts required to serve top $n = n_u n_f$ floors
n_u = Number of cars or operating units in the shafts

As shown above, the operational dispatch interval, $T_{do}(n_f)$, and the round-trip time, $T_r(n_f)$, are expressed as a function of n_p and often must be recalculated several iterations before they reach stable values.

In Equation 10, the number of N-story shafts (shaft group) required to serve top n_f floors, $N_s(n_f)$, is the minimum integer that satisfies:

$$T_{do}(n_f) \leq T_{dr}(n_f) \qquad \text{(Equation 11)}$$

To compute the round-trip time, if the difference between the operational dispatch interval, $T_{do}(n_f)$, and the required dispatch interval, $T_{dr}(n_f)$, is relatively small, it is acceptable to use the average load factor times the capacity of the car, or $n_p = \alpha N_p$ as the number of passengers in the car. However, if the difference is large, the round-trip time must be recalculated using the adjusted number of passengers in the car, n_p, which is estimated from:

$$n_p = \alpha N_p T_{do}(n_f) / T_{dr}(n_f) \qquad \text{(Equation 12)}$$

In a short shaft that serves very few floors, the round-trip time can be very short, even when the assigned shaft for the served floors is only one. In such a case, increasing the number of served floors by the car in the shaft may be considered.

Sometimes the change in the round-trip time changes the number of shafts required. If the number of shafts required, $N_s(n = n_u n_f)$, computed from the new n_p is not the same as that computed from the old n_p, we must recalculate $T_{do}(n_f)$, n_p and $T_r(n_f)$ using the new n_p.

Required Number of Elevator Shafts and Floor Space
Required Number of Elevator Shafts

The number of shafts required in the N-story shaft group in which the zone size is n, the number of top floors served by a car in the shaft is n_f, and the number of operating units in a shaft is n_u, given as the smallest integer that satisfies:

$$N_s(N, n) \geq T_r(N, n_f) / [T_{dr}(n_f = n/n_u)] \qquad \text{(Equation 13A)}$$

or

$$N_s(N, n) \geq T_r(N, n_f) / (300\alpha N_p / D_p \, n_f) \qquad \text{(Equation 13B)}$$

where

$N_s(N, n)$ = Number of shafts required for an N-story shaft group, in which the top n floors is served by the cars in the shaft, and $n = n_u n_f$
$T_r(N, n_f)$ = Round-trip time of a car that serves n_f floors in the top served floors of an N-story shaft group (seconds)
n_u = Number of operating units in a shaft
= 1 in the conventional elevator system
= $m/2$ in a two-car tandem, multiple-car elevator system
= $m/4$ in a two-car tandem, multiple-car elevator system

Required Floor Space for the Elevator System

The total floor space required for the N-story shaft group, $F_s(N, n)$, of which the top n floors are served by the cars in the shaft group, is obtained from:

$$F_s(N, n) = \beta A_s(N + N_{ef}) N_s(N, n) \qquad \text{(Equation 14)}$$

where

β = The coefficient used to estimate the required space for elevator shafts and waiting areas
$N_s(N, n)$ = The number of N-story shafts in the shaft group of which top n floors are served by the cars in the shaft
A_s = The elevator shaft space (sq. ft.)
N = The net shaft height (floors)
N_{ef} = The number of extra shaft floors required for machine room, etc. (floors).

The floor space required at the ground level for the N-story shaft group, $F_g(N, n)$, of which the top n floors are served by the cars in the shaft, is obtained as:

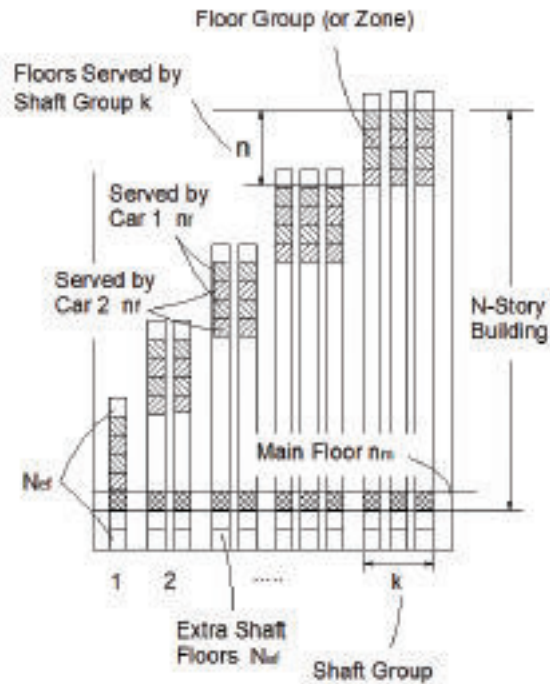$$F_g(N, n) = \beta A_s N_s(N, n) \qquad \text{(Equation 15)}$$

Figure 8: Shaft group design

The terminologies used in this article relate to the shaft group design of a fictitious N-story building, where $N = nk + n_m$ (Figure 8). If a building in which each floor has the same passenger demand from the second floor (or third floor in the two-level lobby system) up, and that the zone size is the same in every shaft group, the total floor space required for an N-story building that has k shaft groups, $TF_s(N = nk + N_m, n)$, is expressed as:

$$TF_s(N = nk + n_m, n) = \sum_{i=1}^{k} F_{s,i}(ni + n_m, n)$$

$$= \sum_{i=1}^{k} \beta A_s(ni + n_m + N_{ef})N_{s,i}(ni + n_m, n) \qquad \text{(Equation 16)}$$

where each shaft group serves n floors at the top of the shaft, and the total floor space required at the ground level for an N-story building, in which each shaft serves the top n floors with k shaft groups, $TF_{g,i}(N = nk + n_m, n)$, is expressed as:

$$TF_g(N = nk + n_m, n) = \sum_{i=1}^{k} F_{g,i}(ni + n_m, n)$$

$$= \sum_{i=1}^{k} \beta A_s N_{s,i}(ni + n_m, n) \qquad \text{(Equation 17)}$$

where
$N_{s,i}(ni + n_m, n)$ = the number of ni-story shafts in the ith group, of which the top n floors are served by the cars in the shaft
$F_{s,i}(N = ni + n_m, n)$ = the total floor space of N-story shafts in the ith shaft group, of which the top n floors are served by the cars in the shaft
$F_{g,i}(N = ni + n_m, n)$ = the total floor space at the ground level of N-story shafts in the ith shaft group, of which the top n floors are served by the cars in the shaft
n_m = the number of floors in the main floor

Numerical Example of Selecting the Number of Floors Served by a Car

This section discusses a study conducted on floor-space requirements and passenger travel time using the conventional elevator system for three passenger demand of 50 passengers per 5 minutes per floor in the peak 5-minute period.

Car and Shaft Designs

The hypothetical 13-passenger and 26-passenger cars used in the experiment have floor areas of 2.24 m^2 (24 sq. ft.) and 4.48 m^2 (48 sq. ft.), respectively. The two car sizes were selected to represent small and large car sizes. The numbers 13 and 26 are the nominal capacity of these cars and were computed from the unit floor usage of 1.8 sq. ft. per passenger. The number of passengers assigned to a car (or design capacity) is α times the nominal capacity, and the crush loading capacity is 1.2 times the nominal capacity (or 1.5 sq. ft./passenger). If the arrival process of passengers at the main floor follows the Poisson process, and the average rate of passenger arrivals is the exact number that makes each elevator car 80% full (the design capacity of the car), and that elevator cars leave the main floor at regular intervals, then for the 13-passenger car, the average number of passengers arriving at each departure is 10.4 (or $N_p = 13 \times 0.8 = 10.4$). (The standard deviation is 3.2.) In the 13-passenger car, mean plus twice the standard deviation of the design capacity becomes slightly over the crush capacity ($24/1.5 = 16$ passengers). In the 26-passenger car, mean is 20.8 (or $N_p = 26 \times 0.8 = 20.8$) (the standard deviation is 4.56), and mean plus twice the standard deviation is well below the crush capacity ($48/1.5 = 32$ passengers).

The 13-passenger car will have a higher chance of leaving passengers behind than the 26-passenger car will.

Even in the 13-passenger car, however, it is rarely expected to see passengers left behind when the car leaves the main floor, because the peak 5-minute demand is used for analysis, and the operational dispatch interval is almost always (and sometimes significantly) less than the required dispatch interval; it means that the average number of passengers in the car is almost always (and sometimes significantly less) than 80% of car capacity.

The shaft area of the 13-passenger car is 4.2 m² for one car per shaft system, and 4.64 m² for two cars or two tandem units per shaft system, and the shaft area of the 26-passenger car is 7.7 m² for one car per shaft system, and 8.4 m² for two cars or two tandem units per shaft system. The number of extra shaft floors used are: two in the conventional system (1/1/1/n/1) – one for the machine room at the top of the shaft and one for the elevator pit at the bottom; four in the two-car-per-shaft system (1/2/2/4/1) – two for the machine room at the top of the shaft, one extra floor for the lower car storage and one extra floor for the

bottom pit at the bottom of the shaft; and six in the two-car-per-shaft system (2/2/4/8/2) – two for the machine room at the top of the shaft, one extra floor for the lower car operation at the ground level, two extra floors for the lower car storage, and one extra floor for the bottom pit at the bottom of the shaft.

How Travel Time and Number of Shafts Required Vary As Number of Floors Served Vary

Figure 9 shows the relationship between the number of floors served (n_f) and the travel-time-related parameters, and the relationship between the number of floors served (n_f) and required number of shafts in the conventional elevator system that uses a 13-passenger car. As the travel-time-related parameters, we selected the round-trip time, the required dispatch interval, the operational dispatch interval, the service time and the average total travel time. Of these, the average total travel time is the key parameter to the passenger. On the other hand, to the building owner, the key parameter is the number of shafts required to serve a floor group. The objective

is to find the number of floors served (n_f) by the elevator cars in the shaft group that minimizes the required number of shafts [$N_s(n_f)$] and, possibly, the average total travel time [$T_t(n_f)$], while keeping the total travel and waiting times at the main lobby within acceptable levels. Figure 9 shows that the operational dispatch interval, $T_{do}(n_f)$, and the service time, $T_s(n_f)$, increase as the number of floors served by a car, n_f, increases. The decrease in the operational dispatch interval is greater than the increase in service time between $n_f = 1$ and 2, and the decrease in dispatch interval and increase in service time is the same between $n_f = 2$ and 3. Thus, the average total travel time, $T_t(n_f)$, becomes minimum (64 seconds) at $n_f = 2$ and 3. The required number of shafts for $n_f = 1$, $N_s(1)$, is two, and the required number of shafts for $n_f = 2$, $N_s(2)$, is four. The required number of shafts at $n_f = 3$ is seven, or $N_s(3)/3 > 2$. It means that $n_f = 2$ minimizes both expected total travel time and the required number of shafts to serve a floor, and the maximum wait time at the main lobby is 30 seconds, which equals the operational dispatch
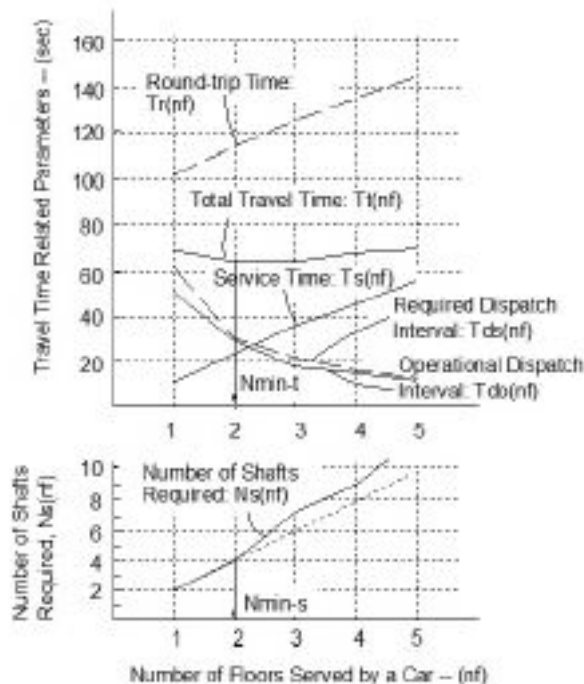

Figure 9: Travel time and shafts required versus number of floors served: (1/1/1/1/n_f/1), 50 stories, 50 passengers per 5 minutes per floor
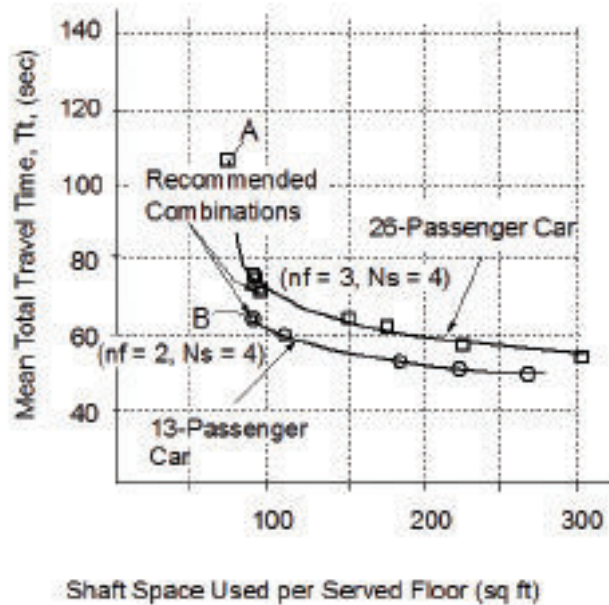

Figure 10: Selection of number of floors served by a car: 50-story shafts and 50 passengers per 5 minutes per floor

interval $T_{do}(n_f)$. Thus, we will select n_f = 2 as the number of floors the elevator car serves in a trip in the morning peak period under the hypothetical conditions.

How Travel Time Varies As Number of Floors Served by a Car and Number of Shafts Used Vary

We conducted further investigations to seek the average total travel time and required number of shafts for various n_f and $N_s(n_f)$ combinations in the conventional elevator system for 13- and 26-passenger cars. We assumed that the maximum wait time limit is 30 sec. Here, the wait time is defined as the elapsed time between the passenger's arrival at the waiting area and the arrival (or opening of the door) of the elevator car.

The two lines in Figure 10 are the results of numerous runs that compute the total average travel time and the required shaft space, indicating the envelope of the "best possible combinations – the shortest average total travel time and the minimum shaft space combinations" of the total average travel time and the required shaft floor space. In the figure, the x-axis indicates the number of floors the car serves, and the y-axis indicates the average total travel time of the passengers. Figure 10 shows that the 13-passenger car will produce shorter average total travel times for any given shaft space or require less shaft space to produce the same average total travel time as the 26-passenger car, even though the two curves become closer as the passenger demand increases and the building height becomes higher. Figure 10 also shows that to produce the same average total travel time, the 26-passenger car requires about 50-100% more elevator shaft space than the 13-passenger car does.

If the space alone, not the travel time, is the issue, the 26-passenger car can perform slightly better as points A and B in Figure 10 indicate, but these points show that the 13-passenger car can reduce the average total travel time by 50% or more, while the elevator system requires slightly more floor space. We would think that a building owner would be willing to spend slightly more on space for a huge improvement in service.

Recommended combinations of n_f and N_s shown in Figure 10 by double circle marks and double square marks are selected from those sets of deemed "optimum" combination of n_f and N_s, and that satisfies the maximum wait time of 30 seconds at the main floor.

How the Multiple-Car Elevator System Compares to the Conventional Elevator System in Tall Buildings

This experiment deals with two types of building designs. The two building designs are the three-layer type, in which the building has two sky lobbies connected to the main lobby at the ground level by express elevators, and the single-layer type, which is of the conventional building structure that does not have sky lobbies. (The expression "three-zone" instead of "three-layer" is more commonly used.) The building that uses the sky lobbies, the 13-passenger car or 13-passenger car tandem units are used for local traffic in each building zone, or the 26-passenger car and 26-passenger car tandem units are used for express systems between the lobbies. In the single-layer building, the 13-passenger car or 13-passenger car tandem units are used. The operational schemes examined follow.

A three-layer building that has two sky lobbies (note that the three-layer building is different from the aforementioned three-layer operation method, in which each car serves a different layer of floors within a zone):

◆ Conventional elevator system – basic operation with one floor (express) zone (1/1/1/1/1) and a two-floor zone (1/1/1/2/1)
◆ Multiple-car elevator system – two-cars-per-shaft, two-layer operation, multiple-car system with a four-floor zone (1/2/2/4/1) and two-car tandem, skip/stop operation with an eight-floor zone (2/4/4/8/2)

A one-layer building that has a one-level main lobby at the ground level:

◆ Conventional elevator system – basic operation with one floor (express) zone (1/1/1/1/1) and a two-floor zone (1/1/1/2/1)

A one-layer building that has a two-level main lobby at the ground level:

◆ Multiple-car elevator system – two-cars-per-shaft, two-layer operation, multiple-car system with a four-floor zone (1/2/2/4/1) and two-car tandem, skip/stop operation with an eight-floor zone (2/4/4/8/2)

Figures 11 and 12 show the required floor space for elevator systems at the ground floor and the whole building, respectively. The figures show that, in both cases, the multiple-car elevator systems require less floor space than the conventional elevator systems, and that the single-layer system is superior to the three-layer one in that none of the people have to transfer to other elevators en route.

The elevator systems used in the experiment are equipped with inter-lobby shuttle elevators between the sky lobbies – three 26-passenger-car shafts in the conventional systems, and two 26-passenger-car shafts in the multiple-car systems — but do not have local elevator shafts for the passengers, whose trips are not lobby based. Thus, they must come down once to the lobby floor and

then take another elevator car. The smaller the zone size, the more frequently this will take place. To avoid this, special elevators may have to be installed in the unused portion of shafts. Inevitably, however, some extra shafts will be needed for reaching the floors in the elevator zones at the top and bottom of each building zone.

The computation results used to create Figures 11 and 12 are not complete – for example, elevator shafts are not grouped together to create a uniform number of shafts to form banks of elevators, shaft heights in each bank have not been adjusted to the same height, no special elevator shafts for non-main-floor-based traffic are considered and no spare shafts are assigned for zones that are served by one shaft only. If these factors are included, the floor requirements are expected to increase by as much as 20% (or even higher in some cases) for all systems.
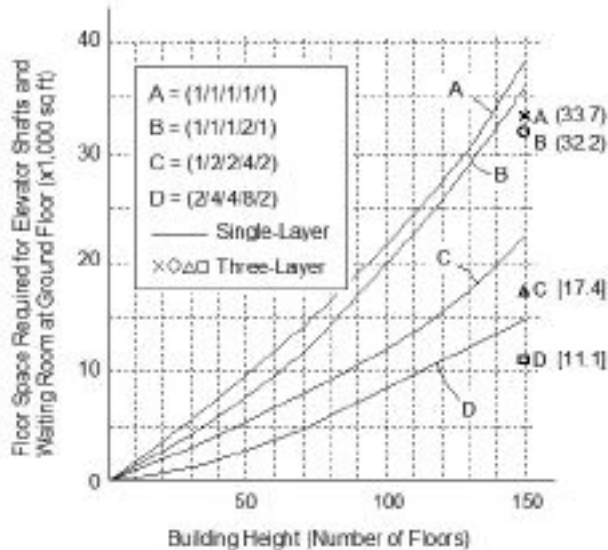

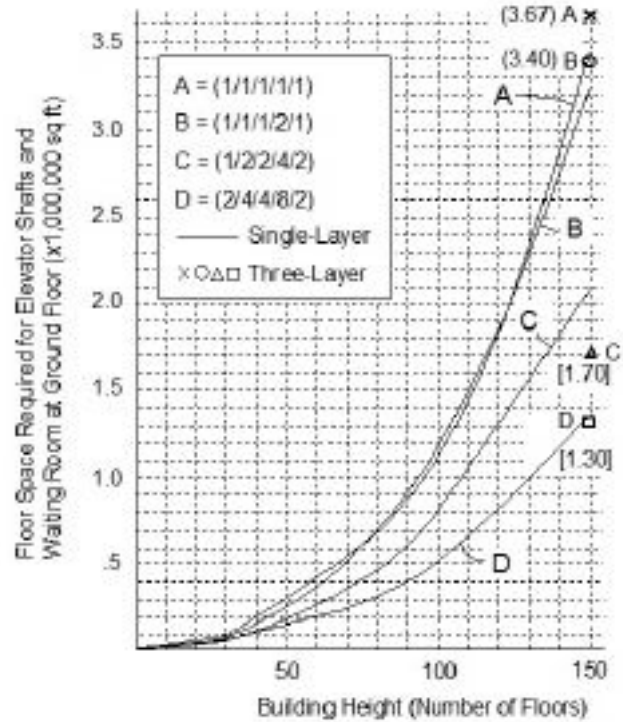Figure 11: Floor space required for the elevator system at the main lobby

Learning Reinforcement Questions

Use the below learning-reinforcement questions to study for the Continuing Education Assessment Exam available online at www.elevatorbooks.com or on page 119 of this issue.

◆ What is the normalized net capacity?
◆ Describe the method of obtaining the round-trip time in the morning peak period.
◆ What are the definitions of the required dispatch interval and operational dispatch interval?
◆ Describe the method to determine the number of shafts to serve n_f floors of a building.
◆ Explain Equation 4 in word form.
◆ Explain Equation 9 in word form.
◆ Explain Equation 10 in word form.
◆ Explain Equation 13A in word form.
◆ Explain Equation 13B in word form.
◆ Explain Equation 16 in word form.

Figure 12: Total floor space required for the elevator system

Conclusions

The study results show that the multiple-car elevator system should be able to reduce required floor space for the elevator shafts and waiting room used by the conventional elevator system substantially in tall and high-demand buildings. The study is based on a limited number of cases based on some arbitrary data, and thus further study is considered necessary.

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[5] Sakita, Masami, "Elevator Control System." U.S. Patent No. 5,663,538, September 2, 1997.
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Masami Sakita is an independent consultant and inventor who works with transportation systems. He holds 20 U.S. patents, including those related to elevator systems and auto engines. His inventions include the multiple-car elevator system, a cat-and-mouse-type rotary engine, and an engine with a variable compression ratio. His recent publications have been in ELEVATOR WORLD and the *Journal of Automobile Engineering*. He holds a PhD from the University of California at Berkeley in transportation engineering.

ELEVATOR WORLD Continuing Education Assessment Examination Questions

Instructions:

◆ Read the article **"Elevator System with Multiple Cars in One Hoistway"** (page 79) and study the learning-reinforcement questions.

◆ To receive **two hours (0.2 CEU)** of continuing-education credit, answer the assessment examination questions found below online at www.elevatorbooks .com or fill out the ELEVATOR WORLD Continuing Education Reporting Form found overleaf and submit by mail with payment.

◆ Approved for Continuing Education by **NAEC for CET® and NAESAI and QEI Services, Inc. for QEI.**

1. In what year did the elevator system that has more than one car in the same shaft first become operational?
   a. 1890.
   b. 1931.
   c. 1995.
   d. 2003.
2. Do the analysis methods described in the article apply to the conventional elevator system?
   a. Yes.　　b. No.
3. How many floors does a car in the (1/2/2/4/1) system serve?
   a. 2.
   b. 4.
   c. 1.
   d. 0.
   e. 2 and 4.
4. In the $(u/c/m/n/f)$ system, what does c indicate?
   a. The number of floors at ground level.
   b. The number of floors served by a car.
   c. The number of floors served by the shaft.
   d. The number of floors served by a car.
   e. The number of floors skipped by a car in the zone.
5. What does the relative normalized net capacity of about four imply?
   a. The shaft has about four times the capacity of a conventional elevator system per unit shaft area.
   b. The shaft has about four times the capacity of a conventional elevator system per unit shaft area, including the extra shaft floors.
   c. A car in the shaft has about four times the capacity of a conventional elevator system per unit shaft area, including the extra shaft floors.
6. What does $t(i = 2)$ represent?
   a. The travel time for a car to travel two floors from start to stop.
   b. That the number of shafts equals two in a shaft group.
   c. The travel time for two cars to travel one floor from start to stop.
   d. The dwell time of a car at the floor in the zone.
7. Why is it important to consider the number of floors served by a car in a shaft?
   a. Because it changes the floor space required for the elevator system.
   b. Because it changes the travel time of the passengers.
   c. Because it is required to do so in the system certification process per Figures 9 and 10.
   d. Both a and b.
8. The larger the car size, the larger the zone size should be from the point of view of shaft space requirement (Figure 10).
   a. True.　　b. False.

9. What may the designer consider if dealing with a short shaft that serves very few floors and the round-trip time is very short, even when the assigned shaft for the served floors is only one?
   a. Reducing the number of floors served by the shaft.
   b. Increasing the number of floors served by the shaft.
   c. Maintaining the same number of floors served by the shaft).
10. A super-high building that has around 150 floors must have a three-layer configuration with two sky lobbies to reduce the floor space used for the elevator shafts and waiting room.
    a. True.　　b. False.
11. In Equation 9, $T_{dr}(n_f) = 300\alpha N_p/(D_p n_f)$. This shows the required dispatch interval, and 300 is the time duration of the peak 5 minutes.
    a. True.　　b. False.
12. If the maximum number of passengers carried in a car, αN_p, is 10 people, and the passenger demand in the peak 5 minutes for the floors served by the car, $D_p n_f$, is 30 passengers, and if the round-trip time, $T_r(n_f)$, is 50 seconds, what is the number of shafts, $T_{do}(n_f)$?
    a. 1.
    b. 2.
    c. 3.
    d. 4.
    e. 5.
13. In Equation 13A, $N_s(N, n) \geq T_r(N, n_f)/[T_{dr}(n_f = n/n_u)]$, what is the difference between n and n_f?
    a. n and n_f both indicate the number of the floor served, and both have the same number.
    b. n and n_f have the same number, but n is used for the number of required shafts, and n_f is used for the round-trip time and the required dispatch interval.
    c. n represents the number of floors served by the shaft, and n_f represents the number of floors served by a car.
14. In Equation 13B, $N_s(N, n) \geq T_r(N, n_f)/(300\alpha N_p/D_p n_f)$, what happens to the number of required shafts as passenger demand in the peak 5 minutes increases?
    a. The number of required shafts increases.
    b. The number of required shafts stays the same.
    c. The number of required shafts decreases.
15. In Equation 14, $F_s(N, n) = \beta A_s(N + N_{ef})N_s(N, n)$, what is βA_s?
    a. β represents extra floor space (for the machine room, etc.), and A_s represents the shaft space.
    b. β represents extra floor space for the waiting room in front of the shaft, and A_s represents the shaft space.
    c. β represents extra floor space for the extra space for the lobby floor, and A_s represents the shaft space.

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