

PUBLICATION

EVACUATION SIMULATION OF TALL BUILDINGS

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ABSTRACT

The evacuation of buildings is mostly based on using the stairs according to the current safety rules. In an emergency situation, elevators are returned to the main lobby and shut down. Special elevators may be reserved for firemen's use to bring up the fire equipment and to help handicapped people. The number of staircases and their width are planned according to walking distances to the exit ways and the floor population. Stair planning and safety codes, however, do not consider the total building population, or the passenger evacuation times from big building complexes. Staircases are often quite narrow and they can easily get congested during evacuation. In tall buildings, only a few people are accustomed to using the stairs. Normally people use the elevators when entering and exiting buildings as a convenient and fast way out.

In this article, a theoretical review of elevator planning and evacuation by elevators and stairs is made. Elevator and stair simulations were made using the Building Traffic Simulator (BTS). A model used to simulate passenger movement in stairs is presented. Passenger behaviour in selecting the fastest way out of the building, as well as considerations of elderly and handicapped people and other passenger groups, are explained. The article shows results of evacuation simulations in some high-rise building complexes. The effect of increasing the number of stairs or using elevators in evacuation is analyzed.

Keywords: Tall buildings, evacuation, simulation, elevators, stairs

1 INTRODUCTION

Most building evacuation plans are based on using stairs only. In case of fire, people on the fire floor and the floors above and below are assumed to use the stairs for evacuation. On other floors, people should stay on those floors until fire is put out. In tall buildings, there can be refuge floors where people can gather during an emergency situation where they can remain until fire is extinguished.

Previous approaches will not offer a solution in emergency situations such as terrorism, nuclear, bomb, chemical or biological threat, or just a situation where a building nearby is on fire. There are also other requirements to evacuate people from a building as fast as possible, such as praying times in Muslim countries. In all these situations elevators are available, and they could be used in evacuation. There has been some discussion on the use of elevators even in the event of fire (Favro 1997; Howkins, 2000). In planning stairs, only the floor population and the walking distances to the stairs or exit routes are considered. No attention is paid to the total population in the building, or how fast people exit the building. These factors become more critical when the number floors in the building increases. Elevators in commercial buildings are planned considering the total population, and normally the transportation time of all people to upper floors is within a 20 to 40 minutes' time frame, which makes them an efficient means of transportation.

According to evacuation tests (Benthorn et al., 1996), the choice of exit is affected by distance and familiarity. People tend to exit the same way they entered, if they do not know the building very well. In emergency situations, however, elevators are most often shut down. In passenger elevators, control systems are prepared to handle emergency situations such as earthquake, fire, power failure and failure situations in the cars. In the event of an earthquake, elevators are usually stopped at the nearest available floor, their doors opened and they are then shut down for some time interval or permanently. In case of fire, passenger elevators are most often returned to the evacuation floor and parked with open doors. Only firemen may use these elevators by a separate key switch to bring their equipment to the upper floors and evacuate disabled people. Firemen may also have their own, fireproof elevators.

2 EVACUATION TIME CRITERIA

The evacuation situation in an emergency situation can be divided into three phases: recognition time, reaction time and egress time. Evacuation time is the total time from the beginning of the emergency until all occupants are in the rescue area. Recognition is from the beginning of the emergency situation to the time occupants become aware of the emergency. Reaction time is the time from awareness to the time persons start to move out from the building. In this article, reaction time means the time delay before all passengers arrive at an elevator lobby or staircase door. Egress time is the period after reaction time that elapses before all the occupants are out of the building or in the rescue area. Passenger waiting time is the time to wait in a queue, and journey time is the time spent in waiting and riding within a transport (see Fig. 1).

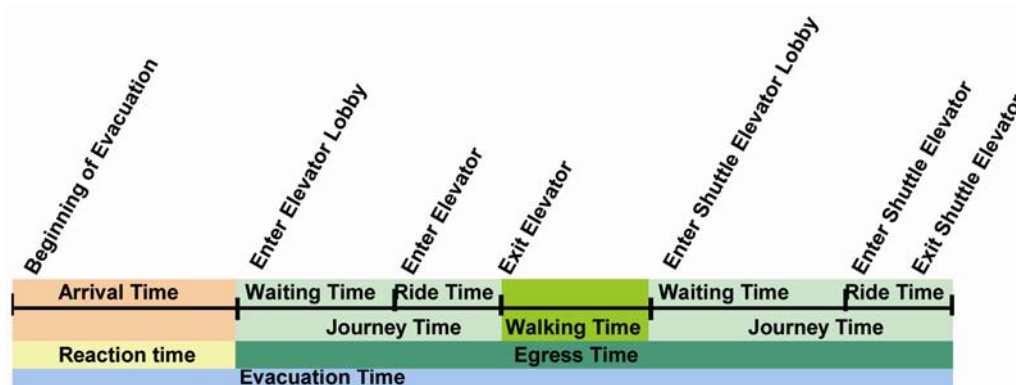


Figure 1. Evacuation time phases in simulation with two elevator journeys

3 ANALYTICAL EVACUATION MODELS

3.1 Stairs model

According to the building codes of North America (Allen et al., 1989) at least two staircases are necessary in tall buildings. Stairs become wider with more population and the number of stairs increases as horizontal walking distances increase. The minimum width is about 1.1 – 1.2 m and two such staircases can serve up to 60 -440 people per floor. The maximum walking distance to an exit staircase must not exceed 30 – 76 m. Two 1.2 m wide stairs fulfil the requirements for most buildings.

In modelling passenger traffic in stairs, flow models are widely used. The models consider passengers as a fluid that flows through passage according to maximum flow. Situations where passenger density is low are called free flow, which means that passengers can walk freely at a defined speed. Traffic flow models are based on the equation

$$F = vD$$

where F is passenger flow per stair or corridor width, v is passenger speed and D is density.

When passenger density becomes very high, complex simulations can provide better results. The problem is that even if physical quantities like pressure and friction can be modelled, human behaviour is difficult to predict. Passenger density and speed are not independent of each other. First, the passenger flow increases with increasing density. At higher densities, however, walking speed is reduced, which decreases the flow (see Fig. 2). The density of maximum throughput is called full flow. Handling capacity calculations are based on the assumption of full flow. Whether the full flow density is achieved or exceeded depends on the building design and motivation of passengers. Therefore, flows that are calculated using handling capacity can be considered as optimistic values.

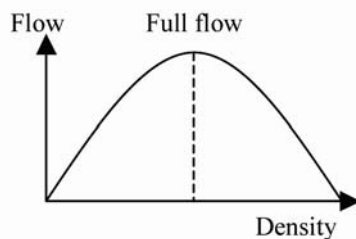


Figure 2. Relation between passenger flow and density in stairs (Weckman, 1997)

In practice, it is easier to measure passenger flow than speed and density. Empirical results of flows in different types of staircases with different riser heights and thread depths exist. Egress time can be calculated simply by dividing the number of passengers on each floor by the passenger flow and width of the stairs. The Melinek and Booth model (Melinek et al., 1975) is an example of flow model.

3.2 Elevator model passenger

A rough way to calculate an elevator evacuation situation is to assume that the elevators serve only one upper floor at a time, the car fills at an upper floor and returns down to the lobby. During a round trip there are only two stops. Elevators travel up and down starting to gather people from the highest floor first, then second highest floor, etc. until all floors are empty. The sum of round trip times and evacuation time for a single elevator, $T_{evacuation}^1$, is

$$T_{evacuation}^1 = \sum_{i=1}^{N_{RT}} (2H_i t_v + 2t_s + 2M_i t_m)$$

[MS1] [MS2] where H_i is the reversal floor index of round trip i , t_v is time to travel one floor distance with contract speed, door and other elevator delays

associated with each stop is t_s , M_i is the number of passengers carried during trip i . t_m is the average time for a passenger to enter or leave the car, and NRT is the total number of round trips needed to empty the building. For a group of N elevators the evacuation time, $T_{evacuation}$, is

$$T_{evacuation} = T_{evacuation}^1 / N$$

If passenger arrival times at elevator lobbies (reaction times) are long, the number of waiting passengers per floor will easily be less than the elevator car size in persons. The elevators will not be filled at one floor so they stop at another floor to collect more people. In this situation, the elevator group control system will decide at which floors the elevators will stop, and the analytical model of Eq. 2 is no longer valid. With modern control systems, collecting passengers in evacuation zones (e.g. one zone every third floor) does not speed up the evacuation process (Siikonen et al., 2002).

4 SIMULATION MODELS

The Building Traffic Simulator (BTS) is a tool for analyzing traffic situations in a building, planning elevators and testing group control algorithms (Siikonen et al., 2001). The main emphasis is on elevator simulations, but other kinds of transportation devices can be modelled as well. BTS is event-oriented discrete event simulator, which means that the simulation of traffic proceeds based on events that are generated when passengers and the devices interact with the simulated environment. The simulator generates passengers that arrive or leave the building randomly according to the Poisson process where all passengers are independent of each other. Passengers travel to their destination floors by walking horizontally or using transportation devices for vertical movement. Transportation device types comprise elevator, escalator and stairs. In elevator groups, real group control systems are used. It is assumed that the transportation devices are the only bottlenecks in the building that may cause queuing. Corridors are not considered. Simulation parameters contain connections and distances between the devices.

In BTS, several tenants, such as offices, residential areas, parking floors, and restaurants, can be defined. It is possible to specify a specific traffic profile for each tenant. In residential buildings, there is a down-peak in the morning while there is an up-peak in an office. Traffic at each moment is divided into four components: incoming, outgoing, intra-tenant and inter-tenant traffic. The portions of each traffic component can be defined in 15-minute periods throughout the day. Incoming passengers enter the lobby and travel to the tenant floors. Outgoing passengers leave the building. Intra-tenant passengers travel within a tenant, and inter-tenant passengers travel between two tenants. In evacuation simulations, however, it is sufficient to use 100% outgoing traffic. In an evacuation situation, passengers accumulate within a short time period, e.g. five minutes. This time is interpreted as an uniformly distributed reaction time for people before they start to egress.

Each passenger belongs to a passenger group, such as child, adult, or handicapped. Different passenger groups can have different walking speeds and space demands. They can also have different preferences of routes. A routing network is created for each passenger group according to the connections. The created passengers use a routing network to reach the destination floor. The arrival, departure, waiting area and stair nodes are included in the network. Each edge contains a travel-time estimate. The shortest path algorithm is used to find the best route. However, travel time estimates cannot foresee waiting times, which are caused by queuing in the future. Therefore, passengers make their final decision based on waiting queues and then change their plans if the original route seems overcrowded.

4.1 Elevator model

When a passenger arrives at an elevator waiting area, he presses the call button and waits until an elevator with the correct direction arrives. When the doors open, he moves towards the door. Entering passengers allow any exiting passengers to come out first. Each passenger causes a transfer time when entering a car. With normal door width (1100 mm), only one passenger can enter or exit at a time. If there is no space inside the car he gives another call after car has left. Inside the car the passenger presses the car call button. The elevator uses defined acceleration, speed and elevator delays, stopping at car calls according to the travel direction. The passenger exits the car when it arrives at his destination floor.

4.2 Stairs model

Passenger traffic in a stair is simulated by a flow model. The parameters of staircase are (effective) width (W), riser height, thread depth and landing length. The effective width is usually a bit less than the physical width since staircases usually have side rails. Even if they do not, people tend to avoid walls. Passenger speed on stairs is modelled in the direction of the slope. Passenger density is defined per floor area in the stair shaft instead of slope area. Therefore, the handling capacity of stairs, C , is 83% of the handling capacity of corridors (Barney, 2003).

$$C = 0.83vDW$$

where

v = passenger walking speed (normally 0.6 m / s)

D = passenger density in stairs (2 persons / m², full flow)

W = width of the stairs

The handling capacity of stairs determines how many passengers per second can pass a fixed point in the shaft; accordingly, it takes $1 / C$ seconds for each passenger, if they pass one by one. The model has four queues on each floor where passengers possibly have to wait (Fig. 3): queues for passengers arriving from up or below, and passengers entering from this floor going up or

down. It is assumed that a passenger can always exit freely, so no delay or queue is needed for exiting passengers. Stairs between two adjacent floors are considered full when the passenger density reaches a maximum value of 4 persons / m².

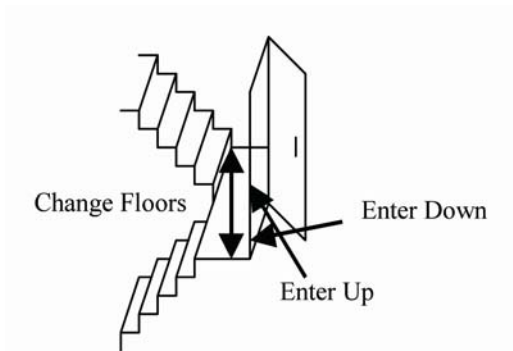


Figure 3. Queuing components for stairs

5 CASE STUDIES

Three evacuation cases were simulated. One of them is also verified by real rehearsal results.

5.1 KONE Building, Espoo

An evacuation rehearsal was made in the KONE Building in October 2002. There were 130 persons in total on 15 floors of the building at the moment of evacuation. All passenger elevators were shut down. One 1.2m wide spiral staircase was used as an evacuation exit. In this type of staircase, at most one passenger fits on one step at a time, since people do not walk on the inner side of the stairs. There was no congestion in the stairs. It took 5 minutes 40 seconds to empty the whole building from the beginning of the evacuation alarm.

The passengers from the highest floor had to walk about 120 meters with the spiral stairs from the height of 54 meters to reach the rescue area on the second level. It is assumed that the effective width is 0.6 m, passenger speed is 0.6 m/s and density 2.0 passengers / m². The handling capacity of the staircase is $C = 0.83 * v * D * W = 0.598$ passengers per second. The evacuation time according to handling capacity is $130 / C = 217$ seconds, which is 3 minutes 37 seconds. The reaction time was about two minutes, which is very short since the floor guards were prepared for the evacuation rehearsal and they knew the rehearsal time in advance. With elevators, the simulated egress time is 3 minutes 24 seconds, which is very close to the time by the stairs.

5.2 Office building and hotel

Two other evacuation cases were simulated.

- a) An office building with 36 floors above the main entrance. The population of the building was 1500 persons, about 50 persons per floor. The average floor height was 3.4 m and the highest floor was 127 m above the ground. In the building a group of seven elevators served the upper floors, and a duplex group served the lower part of the building. The up-peak handling capacity of the seven elevators was 15 per cent of the population in five minutes.
- b) A hotel with 50 floors where three local elevator groups serve the upper part of the building, and a shuttle group brings the passengers from the sky lobby to the ground. The total population at upper floors is 2700, about 100 persons per floor. The highest populated floor is at 172 m and lowest populated floor is at 76 m above the ground at floor 21. The sky lobby is on floor 20, which is served by shuttle elevators. Up-peak handling capacities of local elevator groups are about 16 per cent while handling capacity of the shuttle group is 28 per cent of the population in five minutes.

To calculate analytically the hotel evacuation two 1.2 m wide staircases are assumed. The effective width is 1.0 m, passenger speed is 0.6 m/s and density 2.0 passengers / m². The handling capacity of staircase, C, is 0.996 passengers /seconds (Eq. 4). The evacuation time according to handling capacity is $2700 / 2 / C = 1355$ seconds which equals 22 minutes 35 seconds. The height of 76 meters corresponds to floor 21 and since the walking distance is slightly less than 10 m per floor, the walking time is 16 seconds per floor. Total egress time equals to 1355 + 320 seconds, which is 27 minutes 55 seconds. If the stairs did not become full, the walking time from the highest floor would be less than 13 minutes. The handling capacity is the limiting factor for egress time, not the walking speed. Reaction time was assumed to be short enough that full flow is achieved instantly and no additional delay was induced.

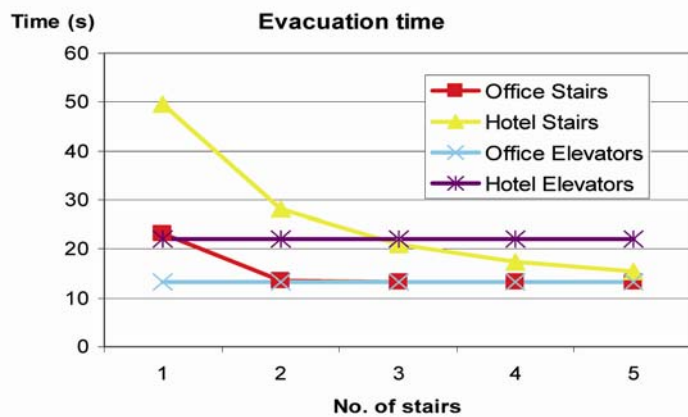


Figure 4. Evacuation times with elevators or stairs in the hotel and office buildings

In Figure 4, egress times with different numbers of staircases are shown. In both buildings, with two stairs evacuation times are longer compared to elevators. Egress time by stairs saturates to a constant value when the number of stairs becomes big enough. In both buildings egress times by three stairs become faster than with the defined elevator groups. In the higher hotel building with more population, egress times decrease until the number of stairs is five or six.

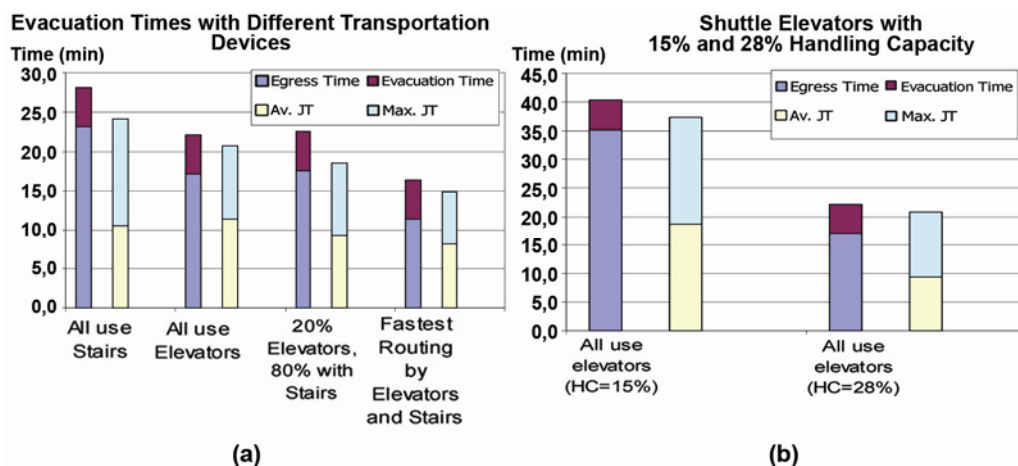


Figure 5. Evacuation times and passenger journey times during the evacuation of a 50-floor-high hotel building

In Fig. 5a evacuation times consisting of reaction and egress times, and average and maximum passenger journey times are shown. The results are simulated with two stairs and with the defined elevator groups in the hotel building. The reaction time was 5 minutes. With two stairs there was congestion and the egress time was about 23 minutes, with maximum journey time of 24 minutes. When using only elevators, the egress time becomes 17 minutes and maximum passenger journey time will be 22 minutes. A

simulation was made where 18 per cent of passengers were assumed to be elderly people or 2 per cent handicapped who could not move on crowded stairs. They used elevators during the evacuation. The space demand of a handicapped person in a car was assumed to be 4 persons, and walking speed of elderly and handicapped people 0.4 m/s. Normal walking speed was assumed to be 1.0 m/s. The total egress time was about 17 minutes, and maximum journey time about 18 minutes. In the last case passengers have selected either elevator or stairs depending on the queue length at the lobbies. The egress time and maximum journey are the shortest. Maximum journey times are in all cases shorter than evacuation times. Average passenger journey time is about half of the egress time.

In Fig. 5b, situations where the handling capacity of shuttle elevators is either 28 or 15 per cent of the population in five minutes, are compared. Elevators for commercial buildings are usually planned for up-peak traffic since it is normally the worst traffic situation considering handling capacity. For shuttle elevators, however, the evacuation situation is the worst traffic situation. In down-peak, local elevators can carry 1.5-1.8 times more passengers than in up-peak to the sky lobby. For shuttle elevators with two stops, up- and down-peak situations are identical. Shuttle elevators should be able to handle the down-peak or evacuation, with 1.5-1.8 times the normal up-peak handling capacity (Siikonen et al, 2002). According to figure, with 15 per cent handling capacity shuttle elevators become a bottle neck to the traffic during evacuation and egress time increases to 35 minutes instead of 17 minutes with the bigger shuttle elevator group.

6 DISCUSSION

At the moment stairs are not planned for evacuating large populations. According to the study, the shortest egress times were obtained if passengers could use either stairs or elevators, and always choose the fastest route by themselves. Only down traffic was assumed, no two-way traffic as there will be in case of fire. If firemen use the stairs when going up, more congestion and much longer evacuation times will result. In real evacuation cases, passengers do not see all the exit ways simultaneously and therefore the distribution of passengers in different exit ways will not probably be even, which causes a lengthening in egress times. This problem could be reduced by making evacuation plans floor-wise, so that people in the lowest floors are instructed to use stairs, and on highest floors the elevators if they are available.

The more people and floors there are in the building, the more stairs are needed to compete with the evacuation times of elevators. In mega-high-rise buildings with 100 floors and about 100 persons per floor, about ten 1.2 m wide staircases are needed for free passenger flow. A staircase with two landings requires at least 14-20 m² floor area (Allen et al., 1989) when a typical passenger elevator shaft requires an area of about 4 m². In planning stairs, also their locations should be distributed so that all stairs do not become unavailable at the same time. Fast evacuation time gives also requirements to

elevators. According to Siikonen et al. (2002), evacuation by elevators becomes faster than with two stairs for buildings with 50 persons per floor when the number of floors exceeds 50, with 100 persons per floor when the number of floors exceeds 25 and with 200 persons per floor the number of floors exceeds only 11-12. In a mega-high rise building, shuttle elevators certainly are the fastest way out for the passengers in the sky lobby. They should be constructed so that they last for the longest time during an emergency situation. The power supply of elevators should be ensured, since after loss of normal power elevators become inoperative without an emergency battery supply or emergency power interface.

7 CONCLUSION

In the study, the effect of the number of stairs was compared with typically planned elevators in 15-50 floor high buildings during down peak. With two staircases in the simulated buildings, evacuation by stairs was slower than by modern passenger elevators. With three or more staircases and using ideal full flow traffic, stairs are faster than elevator groups. If there is enough capacity in the stairs there will be no congestion during evacuation. With congestion in stairs, evacuation times grow fast with passenger density and cannot compete with elevator evacuation times. In evacuating the total population from high rise buildings or highly populated buildings congestion will occur and additional staircases for free flow are needed. They will considerably reduce the rentable space and therefore may not be viable.

According to this study, the fastest way out of a building is to use both stairs and elevators. This is possible if the safety of elevator shafts and lobbies is planned the same way as the safety of stairways. At least there should be enough safe elevators for the use of handicapped and elderly people who cannot use stairs during an emergency situation.

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