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TRANSPORTATION DESIGN FOR BUILDING EVACUATION

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ABSTRACT

Evacuation is currently based on using stairs in most tall buildings. In planning stairs, the height of the building is not considered. This leads to long evacuation times in high-rise and mega high-rise buildings.

The planning of elevators in most tall buildings such as offices, hotels and apartment houses, is based on up peak. No planning criteria for the evacuation time are defined. A risk and threat analysis of the desired security level is one way to set a goal for the evacuation times. Evacuation goals should be established early in the planning phase of a building project, which in turn sets requirements on the buildings spatial organization and its structural and automation systems.

In this article, different scenarios of evacuation are introduced. Definitions and the process of the evacuation concept are discussed. Analytical equations to calculate evacuation times are shown. Simulation is a useful tool for determining the safest and most efficient way to evacuate a building. The building traffic simulation helps to optimise the evacuation concept. In the Kone Building Traffic Simulator (Kone BTS), vertical transportation is configured using actual elevator group control algorithms. Stairs and horizontal movement are also included. Staircases and elevators are compared for some scenarios, and the fastest transportation means are investigated. Evacuation scenarios with different elevator arrangements and control principles are also studied.

1 INTRODUCTION

Traditionally, the egress design of buildings has primarily been targeted in fire scenarios. The sad development of increasing terrorism and acts of violence has brought new threats and risks to buildings and the built environment. Norms on fire resistance and compartmentalization may be inadequate to protect building occupants during the time needed to evacuate of a building in this relatively new situation.

Fire protection and its related egress regulations do not provide enough time for occupants to empty buildings in extraordinary situations. According to EN-72, stairs are considered as the main escape route in tall buildings. During an emergency situation, passenger elevators are returned to the main escape level and shut down. Staircases, on the other hands, are planned according to the floor population and thus more for the needs of a single floor evacuation. The cumulative effect of people in staircases during the evacuation of tall buildings is not considered.

Evacuation time requirements are the main driver in determining other requirements for the emergency evacuation elevator system and its related building components. In this paper we discuss the possibilities to extend elevator functionality for evacuation use.

2 CALCULATION OF EVACUATION TIME

Passenger elevators are usually planned in a building with a certain up-peak handling capacity, for instance in office buildings typically with 12-16 per cent of the population in five minutes (5HC). With 5HC of 15 per cent the building can be filled in about 33 minutes. Down-peak is an easier situation, since 1.5-1.8 times more passengers can be transported with the same elevators. The efficiency factor depends on the control system, typically 1.6 can be assumed. The egress time will be shorter, and with 5HC of 15 per cent the building can be emptied within about 20 minutes. In hotels the typical 5HC varies between 8-12 per cent. In residential buildings the traffic is lighter and typical 5HC values vary between 5 – 7.5 percent. With 7.5 per cent Handling Capacity the building will be filled within 67 minutes, and emptied within 42 minutes.

If the handling capacity of the elevators is known and people have to use only one elevator on their way to rescue area, the egress time given in minutes is

$$T_{Elevatoregress} = 100 * 5 / 5HC / 1.6$$

If the handling capacity of the elevator group is not known, egress time with elevators can be calculated from the round trip time. Let's assume a 16-floor building with total population of 1500 persons that equals to 100 people in 15 upper floors. For handling 15 per cent of population in five minutes in up-peak situation a group of eight cars for 21 persons and speed of 2.0 m/s is required. In heavy down-peak elevators often become full when elevator is loading by

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people from one floor. Elevator round trips consist of two stops, one at the floor to be evacuated, and another at the rescue floor. To empty each floor elevator has to make six round trips assuming that the car is filled to about 80 percent from the nominal car size. Totally 15 floors has to be emptied which makes totally 90 round trips (NRT).

The round trip times for each floor (Klote, 1991, Siikonen, 2002) can be calculated when we know the distance from the rescue floor to the evacuation floor Hi and back, and divide it by the rated speed v. Also the stop times have to be added in the round trip time. Stop time includes door delays (typically 4 seconds) and elevator acceleration and deceleration delays ts associated with each stop (v/acceleration), and delays for the M passengers to transfer in and out from the car (tm typically 1 seconds) during down trip i. The sum of all round trip times is

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

RTT is the egress time of a single car, and for a group of N elevators the egress time $T_{Elevatoregress}$ is

$$T_{Elevatoregress} = RTT / N$$

Equations 2 and 3 are not valid if there are only a few persons per floor and the elevator has to collect passengers from many floors during the down trip. With small floor population gathering of people e.g. to every third floor would decrease the egress time.

Egress time of staircases can be calculated for instance from the handling capacity, C. Staircase handling capacity is 83% of the handling capacity of a corridor (Barney, 2003a), and given in persons per minute is

$$C = 0.83 * (60 * s * D * W)$$

where s is the walking speed of a person in stairs (typically 0.6 m/s), D is density of people in staircases (with full flow 2 persons per square meter) and W is the effective width of the stairs. Egress time is total population A divided by handling capacity C and the number of staircases L.

$$T_{Stairsegress} = A / C / L$$

If it takes a longer time to walk from the furthest floor to the escape level (walking distance/s) than $T_{stairsegress}$ then the egress time in stairs is the longest time of these two.

3 WHAT IS THE TARGETED EVACUATION TIME?

Figure 1 shows calculated egress times with stairs and elevators. Two 1200 mm and 1400 mm wide protected staircases were assumed. Two staircases are the fastest way to evacuate an office building if the population is below 2500-3000 persons in the building. This size of population can be found in buildings with e.g. 25 floors and with 100 persons per floor, or 15 floors and with 200 persons per floor. If a requirement for the egress time is set, let's say to 30 minutes, in an office buildings with more than 3500 – 4000 persons two staircases do not fulfil the requirement. In high-rise office buildings with well planned elevator groups the building can be emptied with elevators within 20-30 minutes if they all are used for evacuation. According to simulation results passenger egress times in a building are about half if both stairs and elevators are used (Siikonen et al., 2002). If the evacuation is time-critical this implies that both stairs and elevators should be used for passenger evacuation.

Figure 1. Egress times with two staircases and typical elevator groups

Figure 1 considers only the egress time in the building, and passenger arrival times to lobbies are not taken into account. Equations 1-5 cannot be used for combined use of elevators and staircases, since people will make their own decisions in choosing the transportation devices, and a way out of the building. By simulating passenger traffic and transportation devices in the building, queuing and waiting at landing floors can be modeled as well as passenger behavior to some extent.

4 GENERIC EMERGENCY EVACUATION SCENARIOS

The goal of emergency management routines and equipment installation is primarily to prevent emergencies from occurring. If the prevention of emergencies fails, the next objectives are detection, response and recovery (BOMA, 2000; Craighead, 2003). These objectives give us the following generic phases of any emergency, which can also be applied to evacuation as shown in Figure 2.

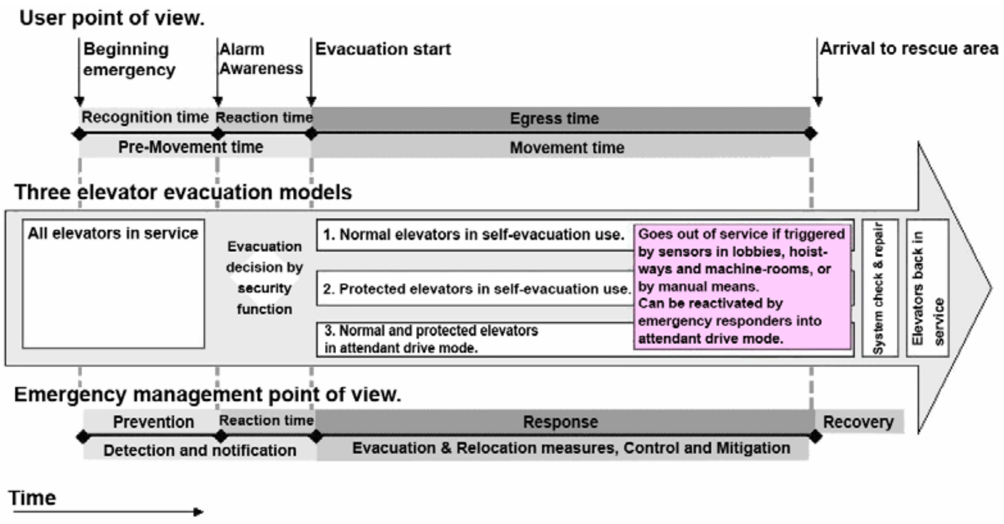

Figure 2. Description of three models of elevator service during an emergency evacuation scenario

Prevention means that the building and its installations are planned and built so that perceived emergency situations are less likely to occur. Preventive measures also include the training of personnel and other people.

Detection of emergencies today consists of installations and various services ranging from the weather service (i.e. hurricane warnings) to security service providers and fire alarm systems.

Response to emergencies means both actions by active systems (like sprinkler systems) and various response routines that are carried out by the building personnel, authorities and tenants jointly and separately. The goal of response is to delay and minimize the impact of an emergency and to enable a fast recovery to normal routines.

Recovery means a set of actions that both the machines and the emergency response organizations of a building carry out in order to restore normal status to the building, so that the tenants' and building personnel's activities can resume their normal everyday courses.

Access control solutions involving elevators solve some prevention issues. Built-in sensors in the emergency evacuation elevator system can be used for detection, and functionality planned for extraordinary situations can be part of the response and recovery actions taken.

From the passenger point of view, an emergency situation can be phased differently, to pre-movement and movement time out of the building (Proulx, 1995) as shown in Figure 2.

Pre-movement time is the time before people start to egress the building, i.e. the time from the beginning of an emergency until the occupants become aware and start to react to the emergency.

Movement time means the time from when people move out of the building until everyone has reached an area of safety.

5 THREE EVACUATION SCENARIOS

In most countries today, elevators are not considered to be part of the egress concepts of buildings. This practice has to be modified if elevators are to be used for evacuation. In self-evacuation, tenant occupants can use elevators for evacuation without rescue responders. In Figure 2 there are three models which all imply slightly different requirements to the building and building installations, including the elevator system.

1. **Normal elevators in self-evacuation use**, equipped with smoke detectors in the lobby, machine room or elevator shaft continue normal operation until they are shut down by a sensor. Upon arrival, the emergency responder organization may or may not assume control of the elevators, by placing attendants in them.

2. **Protected elevators in self-evacuation use**, directed by floor/fire wardens. Upon arrival, the emergency responder organization may or may not assume control of the elevators, by placing attendants in them. Emergency responders can control the elevators manually also after the elevators have been shut down by smoke detection or equivalent system inputs.

3. **Normal and protected elevators in attendant mode**, controlled by trained tenants or emergency responders, when they arrive on site.

5.1 Normal elevators in self-evacuation use

In this scenario evacuation can be started earlier and without the aid and supervision of emergency responders. This enables saving more lives. Drive modes need to be defined for different emergencies, such as fire, earthquake, hurricane, etc. These different scenarios call for slightly different driving speeds and logics. Some scenarios require evacuation up, and others evacuation down, and the rescue floors might vary. The various possibilities mean that the evacuation decision should ideally be made by a trained person, either the chief security officer and/or authority after their arrival.

The requirements for normal passenger elevators involve evacuation algorithms and sensors that monitor the status of the elevator system. To be able to use normal passenger elevators in self-evacuation, they should be equipped with at least the features discussed below.

Sensors in the emergency evacuation elevator lobbies, shafts and machine-rooms are needed so that the emergency evacuation elevator system can turn itself automatically into standby mode (emergency responders' drive mode) if the aforementioned sensors are tripped.

In the self-use mode, group control automatically allocates landing calls to elevators. This is already a feature in standard elevators today and it enables an efficient traffic handling capacity. Additional algorithms include a special evacuation mode. In evacuation mode, group control can determine the order in which the floors are evacuated. For instance, firstly the emergency floor, secondly the upper floors, and at the end the floors below emergency floor are evacuated. The elevator group controller has a built-in capacity to allocate the elevator cars of a group in a most efficient manner so that the waiting time and travel time of the evacuees is minimized. Automatic call allocation is the solution where the evacuation time is critical. In attendant service, each elevator is controlled separately and the elevator attendant has no overview of how to allocate the elevators so that the stops and loading of the elevator car is optimized.

The evacuation mode activation decision requires an active command from a person responsible for security, i.e. it cannot be started automatically by elevator group control system based on automatic inputs. If all elevators are used for evacuation, authorities probably want to restrict the use of elevators so that only professional emergency responders may use them. Reasons for restricting the use of elevators to trained appointed tenants and/or trained emergency responders are: liability/responsibility, safety and normative reasons. The equipment offered by a building should not dictate the emergency response strategies, but simply enable different courses of actions that the emergency response organization undertakes under command of authorities. The evacuation of a building needs to be managed, and it requires adequate communication infrastructure between evacuees and the emergency response organization as well defined and functioning remote monitoring system of elevators. This includes intercom systems, telephone systems and active guidance/signage equipment.

A simulation was made with the Building Traffic Simulator (BTS) to a mega high-rise building that was planned in Asia. There are 88 floors, seven local elevator groups and two sky lobbies with shuttle elevator groups. The 5HC of local elevator groups is about 13 per cent, and the shuttle groups about 17 per cent. In addition there are two 1400 millimeters wide staircases in the building. Total assumed population is 10 700 persons. In the first simulation scenario people use only elevators when going down. People are assumed to arrive at elevator lobbies within five minutes. Simulated evacuation times are shown in Figure 3.

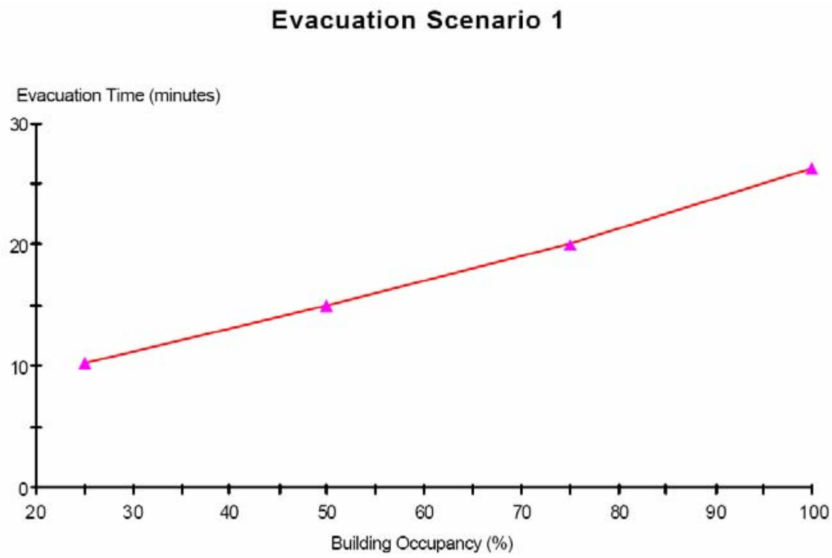

Figure 3. Simulated evacuation times by normal passenger elevators with growing building occupancy ratio.

5.2 Protected elevators in self-evacuation use

A prolonged use of normal elevators during a fire and possibly other scenarios requires compartmentalization of elevator lobbies, shafts and cars together with redundant exit routes connecting to lobbies. The requirements of protected elevators concern their robustness, which has to be added to the requirements of normal passenger elevators defined in the previous section. Protected elevators in U.S. (Bukowski, 2003) and robustness and redundancy features (Klote, 2003) have been researched and published in detail in many articles. In the following some of these features are briefly described.

The protected emergency evacuation elevators require protection against the water used to extinguish the fire. This includes the electrification on landings, in the hoist way, the elevator car and the machine-room. Redundant electrical power sources are needed, which can be either redundant fire-protected electrical power feeds or generators in the machine-rooms. The reserve electrical power should be sufficient to ensure the intended elevator traffic handling capacity. In addition the provision of clean, unspoiled air to the shaft, lobbies and elevator cars has to be provided. This air supply includes the filtering capacity in case of toxic agents and known biohazards. Sensors that monitor the status of the protected elevators are required in order to verify system reliability during evacuation mode and to ensure that the elevators do not stop on floors where the lobby is on fire.

In the second scenario the shuttle elevators are protected in the same building as in Section 5.1. During the evacuation people use stars to get to the sky lobbies that are used as refuge areas. The protected shuttle elevators bring people down to the ground floor from the sky lobbies. Figure 4 shows

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evacuation times for this scenario compared to the first scenario. Evacuation times in Scenario 2 are 1.5- 2 times longer than in Scenario 1.

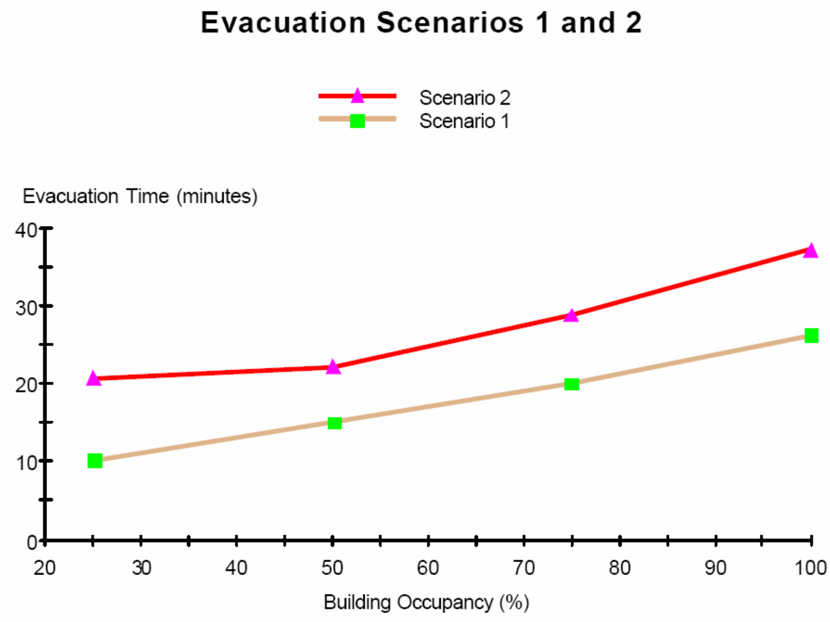

Figure 4. Comparison of simulated evacuation times by elevators (Scenario 1) and by a combined use of stairs and protected shuttle elevators (Scenario 2).

5.3 Normal and protected elevators in attendant mode

At the moment protected firefighters elevators are used in many countries in Europe. According to EN-72, which supports the essential requirements of the EU directive, buildings exceeding 30 metres in height (according to BS 5588:Part 5, 18 metres above and 9 metres below the main access level) require a firefighters' elevator. The number and location of the firefighters' lifts are determined by national regulations. Only firefighters' elevators can be used in an emergency situation with manual drive, other elevators are shut down. The fundamental requirements for the firefighters' elevators (Barney, 2003b) are

- they should serve every floor in the building
- travel time from the lowest to the highest floor should not exceed 60 seconds
- typical load in Europe is 630 kg (8 persons)
- protected lobby and machine room for fire resistance of at least two hours
- water protection for the equipment

- they should have a second protected power supply
- attendant service with one car call at a time
- capture switch at the main access level
- communication system
- emergency trap door

Typically there are one or two firefighting elevators in a building (one for 900 square metres of occupied space). The main task of firefighting elevators is to bring the fire equipment to the bridgehead close to the emergency floor, and for transportation of disabled people. The handling capacity of a typical firefighters' elevator is about 25 disabled persons within half an hour if a firefighter drives the elevator to an upper floor and brings disabled passengers to the rescue floor. Firefighters' elevators do not provide an answer to the building population evacuation needs.

If there are only one or two protected elevators in attendant use, it has no significant effect to the evacuation times of the whole building. Major part of the population has to use stairs. That is why in the third simulation scenario people use only stairs. The results of the three scenarios are shown in Figure 5. In this third scenario people have to wait at upper floor a long time before they can enter the shaft. Evacuation times in Scenario 3 are about five times as long as in Scenario 1.

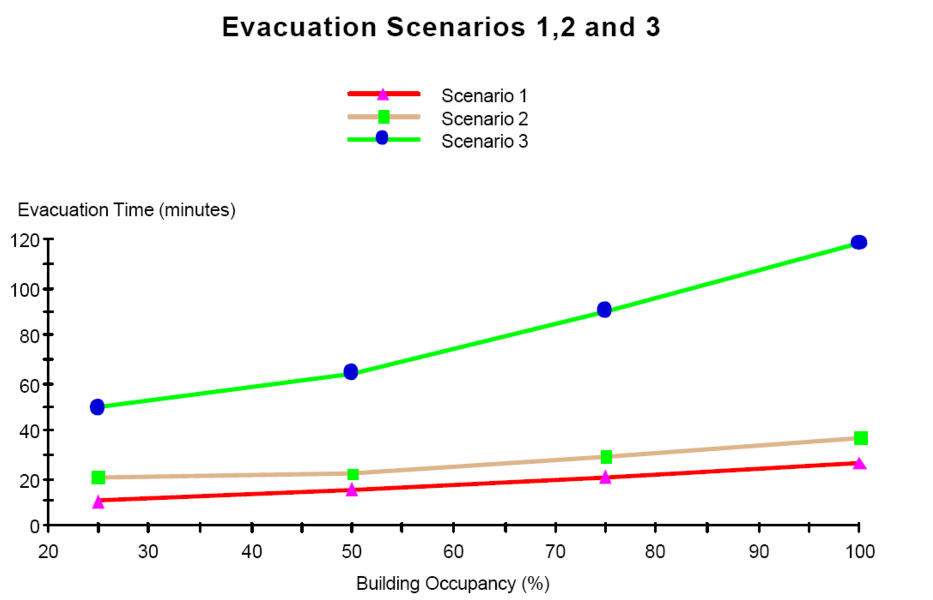

Figure 5. Comparison of simulated evacuation times by elevators (Scenario 1), by a combined use of stairs and protected shuttle elevators (Scenario 2), and by using only stairs (Scenario 3).

6 DISCUSSION

In planning new standards for emergency evacuation in buildings, a time criterion for the evacuation time should be defined. In this way the requirements for the emergency evacuation elevator system and its related building components will be defined as early as at the building planning stage. The possible users of an emergency evacuation elevator system have to be defined as well. Evacuation elevator systems can be intended only for certain user groups or for the whole building population.

Elevators are planned mainly for the up-peak traffic, not down peak and evacuation. With an up-peak handling capacity of more than 12.5 per cent of the population in five minutes, an egress time shorter than half an hour can be guaranteed with elevators. If all passenger elevators were protected for half an hour evacuation, practically all occupants of the building could be rescued.

If only some of the elevators are protected, these should be the elevators that serve the upper floors of buildings. People close to the main entrance floor or refuge floors should be encouraged to use stairs. In mega high-rise buildings, people from the upper floors served by local elevator groups should be encouraged to use both stairs and elevators to get to the sky lobby, that should be planned as a refuge/rescue area (Fortune, 2002). Protected shuttle elevators should be able to empty the sky lobby of the population from the local groups within a certain time, e.g. 30-40 minutes.

Safety issues or authorities can require that the elevators have to be driven manually by either trained local authorities or by trained tenants. If the evacuation time is not time-critical, it can be conceived that either local authorities or trained persons in charge of tenants perform the evacuation drive by elevators.

If only emergency responders are able to give commands from the elevator cars, handling capacity of the elevators will be reduced compared to a situation where the elevator control system automatically dispatches cars according to predetermined evacuation principles. Manually performed evacuation by elevators is better suited for single rescue missions than for actual evacuation purposes, especially in buildings with large populations.

Redundant egress routes are required which are accessible from the elevator lobbies so that passengers can use alternative routes of exit when the elevators are no longer in service. Redundant egress routes from the elevator cars are required in case the elevators are jammed between floors. Whether these should be used only under the direction of emergency responders needs definition.

7 CONCLUSION

In this article, evacuation time criteria were discussed. The height of buildings where evacuation by elevators becomes faster than by stairs was shown by means of a graph to help determine the buildings where elevator protection is needed for evacuation, and when evacuation by stairs is fast enough to meet the criteria. In mega high-rise buildings, the handling capacity of shuttle elevators should be planned according to a defined evacuation time.

The basic requirements of elevators for use in evacuation include prevention, detection, response, and recovery functionality. Some of these requirements can be met by other building systems, structures and human resources. The use of elevators in extraordinary situations requires the training of people in the building.

Three evacuation scenarios were introduced. Evacuation of a mega high-rise build ing with 88 floors was simulated by BTS for three imaginary scenarios. According to the simulation results, if people use two stairs for the evacuation, it takes about five times as long as if they could use the passenger elevators. A significant improvement in evacuation time is obtained if the shuttle elevators are protected and they can be used for the egress in addition to the stairs. Evacuation time is only 1.5-2 times longer than the time when using merely elevators for the egress. In the simulation scenario 2, people used stairs to get to the sky lobbies and then protected shuttle elevators to get down to the main entrance. In the specified mega high-rise building evacuation time can be decreased to 30-40 minutes by protected shuttle elevators, or by increasing the number of staircases to five.

The requirements on operation mode, automatic or manual, have a significant effect on the traffic handling capacity of the elevator system. The shuttle elevators should use automatic group controls since they are more efficient in evacuation compared to attendant service.

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