

*by Marja-Liisa Siikonen and Tuomas Susi of KONE Elevators and  
Henri Hakonen of the Helsinki University of Technology*

The first elevator traffic simulators were developed by a combined relay and computer technique for tall buildings, such as the World Trade Center in New York<sup>3</sup>. The traffic in the whole building was modelled. In the 1970s, the first software-based elevator traffic simulators were developed with computers<sup>7</sup>. In the middle of the 1980s, the first PC-based simulators were developed. These simulators usually involved a single elevator group, and generic control algorithms were used. Only elevator companies had simulators for real control systems. In KONE Advanced Lift Traffic Simulator (ALTS) software<sup>8</sup>, real group control algorithms were used, the same as is used in elevator products. Currently, tall buildings and even mega-high-rise buildings are being planned. The interaction of different transportation devices and their effect on passenger service can now be determined with a new tool, Building Traffic Simulator

## BTS ARCHITECTURE

Because of the need to run in a well-known platform, Windows NT and Windows-specific technologies such as COM and ActiveX were chosen. COM is a binary component architecture for Windows, which makes it possible to change one module without recompiling the whole software. Portability is achieved by separating the code into portable and non-portable components.

Non-portable components contain the main program, the user interface, displays, database interface components and generally everything that is dependent on Windows-specific libraries. These components were developed in the quickest way possible and are mostly written in Visual Basic.

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```

graph TD
    BTS[BTS main program] --- DBR[Input DB reader]
    DBR --- ID[(Input database)]
    BTS --- Timer[Timer]
    Timer --- EGV[Elevator group views]
    Timer --- DBW[Output DB writer]
    DBW --- OD[(Output database)]
    Timer <--> EB[Event buffer]
    EB <--> SC[Simulator core]
    EB --- BV[Building view]
    SC --- EGC[Elevator group controls]
  
```

Legend:

- Event request (blue arrow)
- Event flow (red arrow)
- Other interface (black line)
- COM component (green rectangle)
- Other modules (green cylinder)

# Passenger Traffic Flow Simulation Continued

ven. Events are small pieces of information with a time stamp like "Time: 12s - Elevator two stops to floor five." The timer asks for events of the next time step from the event buffer. The event buffer immediately gives the events stored in it and runs the simulator core until the buffer becomes full again. The event buffer stores events temporarily so that simulation can be displayed smoothly

with different view-components regardless of the processor usage. During the simulation, events are logged in an output database. The output database is used to show statistical outputs and playback after the simulation.

## CONSTRUCTING A BUILDING

The BTS interface has a building design view for constructing a specified building. The user can draw the floor shape of the building for each floor or only the floors where the building shape is changed. The elevator and escalator groups can be dropped in their correct positions on the floor (Figure 2). The primary purpose of this design is to define the shape of the building to make the 3-D animation resemble the real building. During the simulation, distances of the transportation devices affect the passenger walking times between them.

The actual parameters for the building, elevators, escalators and passenger traffic are defined through a simple Microsoft Access interface. The main adjustable parameters are shown in Table 1.

For the building, the number of floors and each floor height are given. A building occupied by several companies can be divided into tenants. Many parameters earlier related to elevator groups are now related to tenants. Though BTS tenants are generally used to represent real-life tenants, they can be used more generally. The tenants may be thought of as areas in the building where certain parameters hold. The population distribution of a building is defined for each floor. In BTS, population distribution is both floor and tenant related. Although the single-tenant floor is the most common type, each occupied floor can have its occupants split between different tenants.

There are several technical parameters that relate to the elevator groups. Nominal speed, acceleration and jerk, as well as door opening and closing times, are given as constant values. Advance door-opening

Figure 2. Design view of the BTS simulator

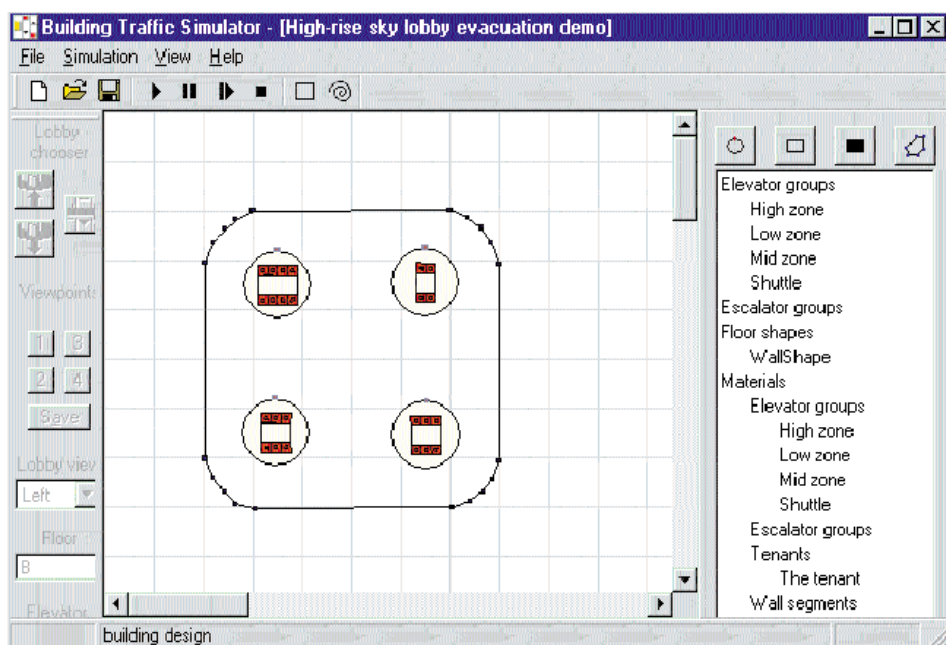


Table 1: Parameters to be defined before the simulation

Building Parameters	Elevator Parameters	Escalator Parameters	Passenger Traffic Parameters
Number of floors	Number of elevator groups	Number of escalator groups	Arrival rate as a function of time
Floor heights	Number of elevators in each group	Number of escalators in each group	Incoming, outgoing, intra-tenant and inter-tenant traffic components for each tenant
Floor names	Nominal speed	Speed	Passenger group
Tenants	Acceleration	Width	Passenger transfer time
Population on each floor	Jerk	Angle	Passenger walking speed
	Start delay		
	Advance opening distance and speed		
	Door opening and closing times		
	Photocell delay		
	Rated and bypass loads		

means that elevator doors start opening before the car has reached the level. This happens when the speed of the elevator and distance decrease below specified values. After each passenger transfer, there is a photocell delay before the door starts to close. Cars can be filled up to the rated load. If the load exceeds the bypass load value, no new landing calls are allocated to the elevators. The waiting area in front of the elevators is so close that no walking time is assumed between the waiting area and the elevator. Only passenger transfer times are used when entering and exiting a car. All the passengers are assumed to fit in the area, which is the case in ordinary traffic situations. If the keypad is located far from the elevator group, waiting times in front of the keypad, and passenger walking times from the keypad to the elevator waiting area are modeled.

Escalator groups are defined by the speed, width and angle of the escalators. These parameters determine travel time and capacity. If the flow of passengers exceeds the capacity, a queue is formed at the waiting area in front of the escalator. The passenger walking times between the transportation devices are considered for each passenger journey.

Passenger traffic is usually given as incoming, outgoing and inter-floor traffic components. In BTS, the traffic components are defined on a per-tenant basis, not per-elevator group. BTS defines four traffic components for each tenant: incoming, outgoing, intra-tenant and inter-tenant. The incoming component simply refers to passengers entering the elevator group from an entrance floor. The outgoing component is analogous to incoming: outgoing passengers are those heading out to the entrance floor. The intra-tenant traffic component refers to passengers that travel inside that tenant's area and do not enter or leave the area served by the elevator group. Inter-tenant passengers leave from tenant A to an "external" tenant B, such as a restaurant, and return back to tenant A again. Several elevator groups may serve the "external" tenant, and a tenant may have inter-tenant traffic with more than one external tenant.

Each traffic component is given as a percentage of the arrival rate to the tenant. The passenger arrival rate is given in the number of passengers per five minutes, or as a percentage of the population within the tenant per five minutes. All traffic components and arrival rates are time-dependent. The total simulation time can be split into arbitrary time slices with different traffic components and arrival rates. Each tenant has time slices of its own. With the time slices, a 24-hour traffic period in a building can be simulated. Instead of a 24-hour simulation, several simulations can be run in series with different traffic intensities for some traffic pattern. This helps to identify the traffic intensity where

the handling capacity of the elevator group is reached with the specified traffic pattern.

Each passenger belongs to a passenger group. Examples of typical passenger groups are adults, children, disabled people and senior citizens. Each passenger is visualized by shape and color according to a passenger group (Figure 3). Passenger group defines the movement speed of a passenger, the space demand in the lobby and inside the elevator. The percentage of passengers in a passenger group can be defined for each tenant separately.

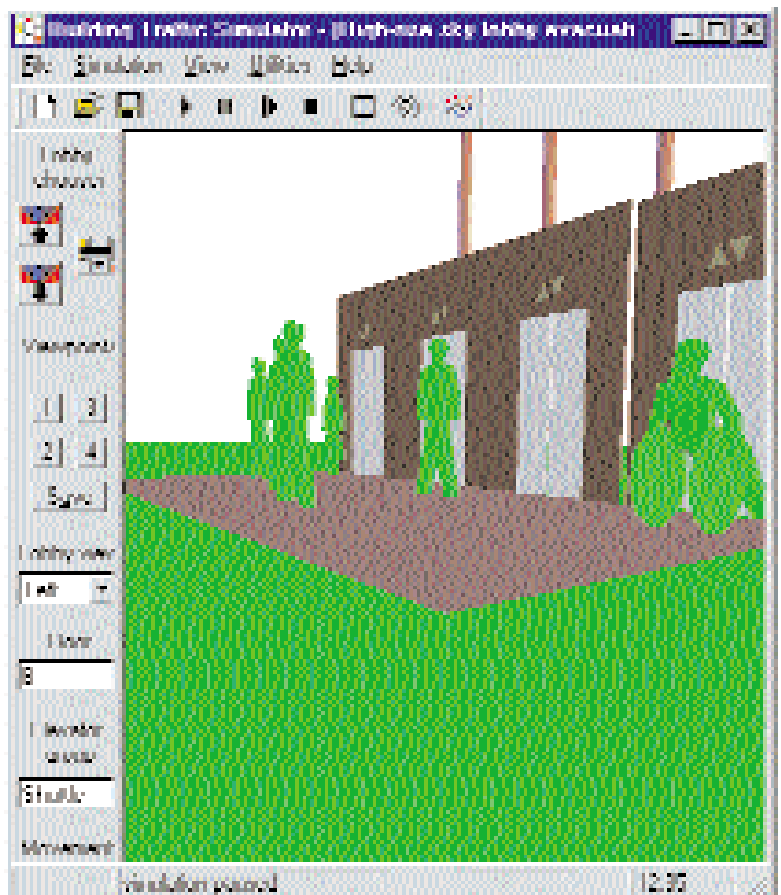
#### PASSENGER GENERATION AND ROUTING

Passenger arrival and destination floors, as well as arrival time, are generated with a pseudo-random number generator. The arrival and destination floors, and possible "external tenant floors," are generated according to the population distribution and traffic components. If a component is inter-tenant, incoming and outgoing components are used as weights to create the departure and destination tenant floors. Global traffic intensity and arrival rate define the number of generated passengers of a given time slice. Arrival times are assumed to be equally distributed between the start and end times of each time slice. The passenger group is selected at random but weighted with the tenant's passenger group distribution.

Passengers may need to use several elevator or escalator groups before entering their destination floor. If the

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Figure 3. Lobby view with typical passenger groups





# Passenger Traffic Flow Simulation Continued

passenger is allowed to change a transportation device at every floor, the number of possible passenger routes is huge. Therefore, a passenger is only allowed to change the transportation device at transfer floors, and only to a transport device that has a connection with the current device.

Passenger routing is done before the simulation. It calculates the quickest route from and to every floor and stores the routes in memory. The routes are calculated with a breadth-first-search of all possible routes from the arrival floor to the destination floor. First, the routes with the least amount of transport changes are chosen. If there are two routes with an equal number of changes, the route with the shortest walking distance and journey time is chosen. Should there still be more than one route left, the passengers are randomly distributed among these routes.

## ELEVATOR DYNAMICS

The travel distance, speed and acceleration of an elevator are calculated from the equations.

$$\begin{aligned} ds / dt &= v \\ dv / dt &= a \\ da / dt &= k \end{aligned} \quad (1)$$

Equation (1) is discretized using the four-step Runge-Kutta method<sup>6</sup>, and elevator position and speed are updated for every time step during the simulation. In the

equation,  $s$  is the travel distance,  $v$  is the speed,  $a$  is acceleration and  $k$  is jerk of the motor. Figure 4 shows the performance of these parameters during one run.

## ELEVATOR GROUP CONTROLS

An elevator group is an independent unit, which is controlled by a group control algorithm. In BTS, different group control algorithms can be applied. Both the simulator and KONE control algorithms rely on PC technology, and the group control algorithms in the simulator are exactly the same as are used in KONE products. Also, new control algorithms can be tested with the simulator. Two of the control algorithms, Enhanced Spacing Principle (ESP) and Genetic algorithm (GA), are described below.

ESP is based on the collective control principle, and it optimizes passenger-waiting times. The number of waiting passengers behind each call is predicted according to statistical data. The landing calls where the number of waiting passengers is greatest gets the quickest service.

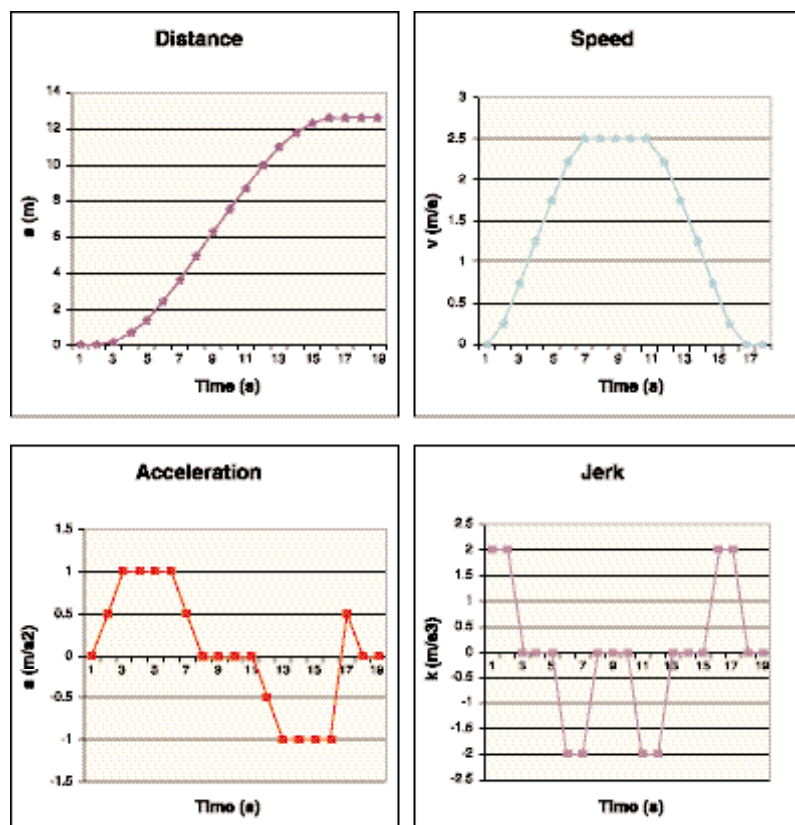
The idea of genetic algorithms comes from natural evolution. They are widely used for difficult combinatorial optimization problems, where exhaustive search is not reasonable. GAs do not guarantee finding a global optimum, but for real-world applications, the solutions are quite close to it. In an elevator control system, GA is used to find the best routes for elevators to serve the existing landing calls.

GA starts from some initial set of routes called *initial population*, which is usually generated randomly<sup>5</sup>. Each solution is coded into a bit string that is called a *chromosome*. In elevator control, each gene in the chromosome refers to an allocation of a landing call to a car. The quality of the chromosome is called *fitness*. The algorithm runs generation by generation using reproduction, crossover and mutation to form the next generation from the fittest routes, e.g., routes with the shortest passenger waiting times. Crossover is done by selecting two chromosomes (elevator routes) and combining them randomly into a new one. Mutation is done by changing bits randomly. The algorithm continues until it decides that the process has converged and then picks the best chromosome for the solution.

## SIMULATOR OUTPUTS

Animations are useful for checking the correctness of the model. If something is missing or some parameter is clearly wrong, it is easier to notice the bug by watching the animation than reading statistics. One can also notice if the ele-

Figure 4. Typical values for drive system parameters during one run



vator system is clearly insufficient or oversized. Often, one has to demonstrate a model to persons who are not experts in traffic calculations. In this case, a good animation is more illustrative and convincing than statistical figures.

BTS has two animation screens. One is a two-dimensional traffic display that shows the traffic events for one elevator group. The screen updates the positions of elevators, active calls and passenger queues. The other is a three-dimensional animation that shows the whole building. In 3-D view, the user can zoom in to certain elevator groups and floors and change the angle of view. The animation shows the shape of building, floors, elevators and passengers (Figure 5).

While animation gives a quick view of what is going on in simulation, numerical data to evaluate the performance of the system more accurately is needed. Statistical outputs give answers to many important questions, such as how long a passenger has to wait for an elevator, how long the whole passenger journey lasts, how fast the building is filled or evacuated and what the assumed energy consumption is. From the studies it can be decided, for instance, how many people in the building can be served by the defined transportation devices, and if the current elevator arrangement is sufficient for

the assumed population. The ordinary performance measures are:

**Waiting time:** Waiting time begins when a passenger enters the device waiting area and ends when he enters the device.

**Passenger journey time:** Journey time starts at the same moment as waiting time, and ends when the passenger exits the transportation device. Also, **total journey time** from the arrival floor to the destination floor is found out if the passenger uses several transportation devices.

**Call time:** Call time starts from registering a landing call until the call is cancelled while elevator decelerates to the landing floor.

**System response time:** System response time starts from registering a landing call until the responding elevator doors begin to open.

**Cycle time:** Cycle time is the average time between two consecutive starts of an elevator. The time the elevator is vacant (when it is stopped and nobody is getting in or out) is excluded from the cycle time.

**Roundtrip time:** Roundtrip time consists of up-and-down trip times. The up-trip time starts when the elevator starts running upward and ends when the elevator reverses direction. The down-trip time consists of the time the elevator travels downward until it reverses direction. The time periods during which the elevator is vacant are excluded from the roundtrip time.

**Energy consumption:** Energy consumption can be computed for each elevator run. The elevator direction, load and travel distance affect the energy consumption.

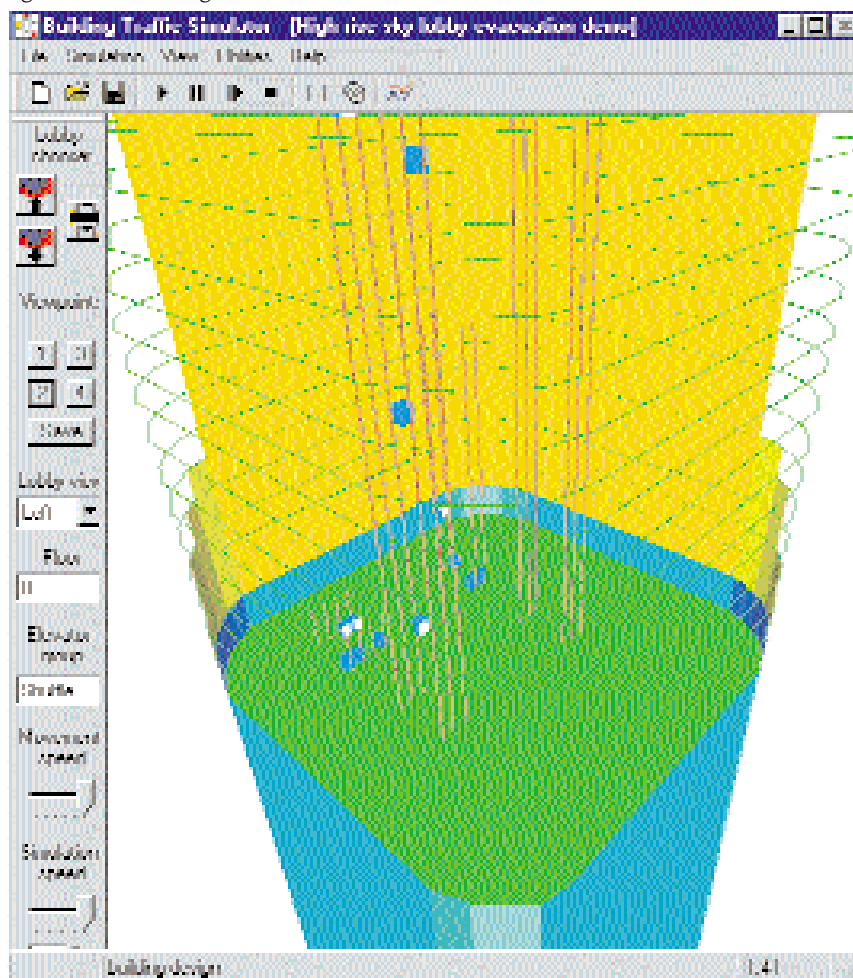
The performance measures for an escalator system are the number of transported passengers, number of starts, idle time and energy consumption.

## CASE STUDY - EVACUATION OF A BUILDING

The sudden need to evacuate a tall building can appear under conditions of emergency in tall buildings. Reasons for a sudden evacuation can include bomb threats or an earthquake. In case of fire, normally it is stated that people should not use elevators. The reasons for this are that elevators may become death traps, elevators are needed by firefighting forces and elevators may be too slow to evacuate people in danger. However, some studies have shown that evacuation of a building with elevators can be rather fast. By using three floor-evacuation zones, people can be evacuated

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Figure 5. BTS building visualizer



# Passenger Traffic Flow Simulation Continued

within 30 minutes in typical high-rise buildings of 20 to 50 floors in San Francisco<sup>2</sup>. An evacuation time of 15 to 30 minutes can be considered to be acceptable<sup>9</sup>.

A case study is made for how fast the upper part of a mega-high-rise building can be evacuated by elevators. The building is more than 400 meters high and has three local elevator groups on the top of the building. All local elevators leave from the sky lobby on floor 53 and serve floors 54-88. The population in the area of the three local groups is about 4,000 persons. A shuttle group of eight double-deck elevators handles the traffic between the ground floor and the sky lobby. The up-peak handling capacities of the local groups for the low-rise are 14%, mid-rise 15% and high-rise 13% in five minutes. This means that all populations can be transported from the sky lobby to upper floors within 33-to-38.5 minutes. The handling capacity of the shuttle group is about 16% of the population above the sky lobby. With the shuttle group, the population of the upper floors can be transported up or down within 31.5 minutes.

In the study, it is assumed that all people in the building get an announcement of the evacuation at the same

instant. All the people of the building arrive at elevator lobbies within one minute and travel down to the ground floor as fast as they can.

In the down-peak situation, even without any zoning, local elevator groups can transport more passengers within a defined time than in the up-peak situation. According to a simulation of the evacuation situation, the low-rise group transported all passengers to the sky lobby within 13 minutes, the mid-rise group within 15 minutes and the high-rise group within 16 minutes. During the simulation, about 1,300 passengers arrive from the upper floors to the sky lobby within five minutes. This corresponds to 33% of the population in five minutes. The maximum number of waiting passengers in the sky lobby is about 2,000 persons. The shuttle group handled the passengers down to the ground floor within about 30 minutes. If the shuttle group had the handling capacity of about 30% of the population in five minutes, it could transport all arriving passengers without queue formation at the sky lobby.

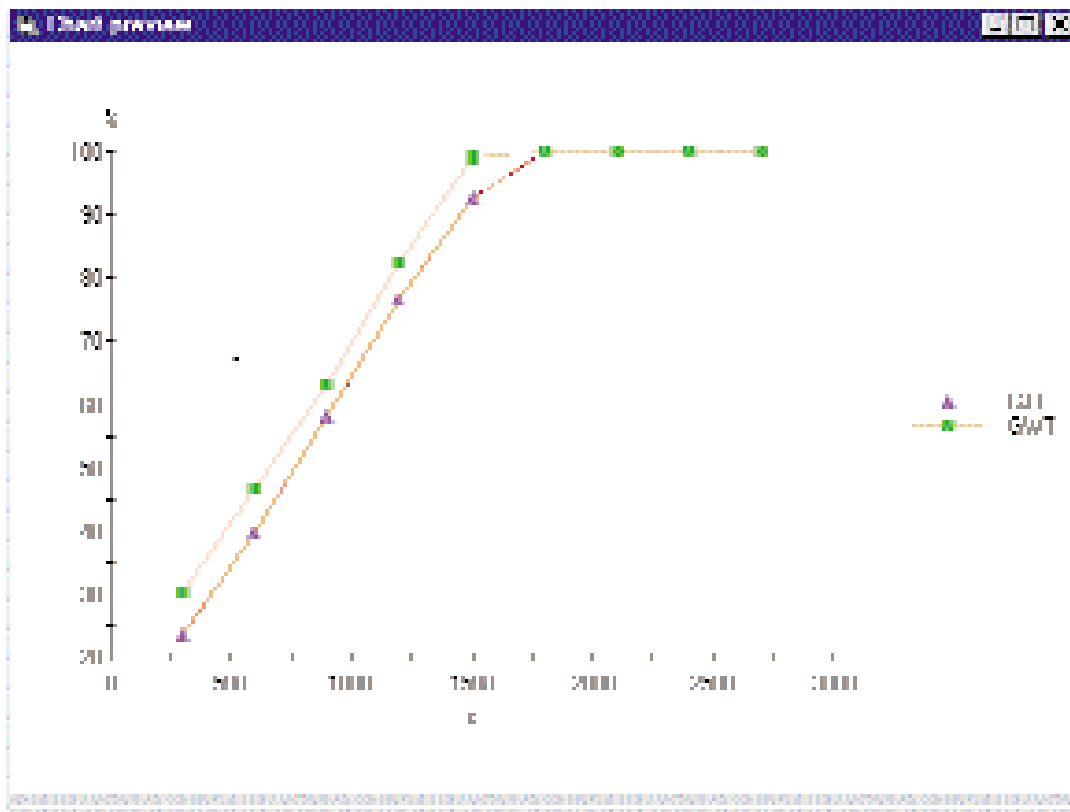
Evacuation of the building on foot using the stairways is slower, and may come to a complete stop causing

panic. For a one-meter-wide stairway, and a full flow of two passengers per square meter with the average speed of 0.6m/s, the passenger flow rate is 60 persons per minute<sup>1</sup>. With about 120 persons per floor and one stairway per floor, evacuation from the first floor lasts about two minutes, and from the 88th floor about 176 minutes, nearly three hours. For an evacuation time of half an hour, six such stairways per floor are required.

## CONCLUSION

The Building Traffic Simulator introduced in this article offers a unique tool for studying evacuation and traffic interaction in any tall building with many transportation device groups. The evacua-

Figure 6. Average waiting and journey time distribution during the evacuation run. GWT refers to percentage of passengers that have waited less than the defined time, and GJT refers to the percentage of passengers served within the defined time.



tion of the 35 highest floors of a mega-high-rise building was studied with BTS. Passengers have first to use a local elevator group, and then a shuttle group to get to the ground floor. The study showed that the assumed 4,000 passengers can be evacuated within about half an hour, which can be considered as an acceptable time. During the emergency situation, a crowd of 2,000 people is formed in the sky lobby. Crowding can be avoided by control means, such as by delaying the local elevators at upper floors. If the defined shuttle group had more handling capacity, e.g., if double-deck elevators were replaced with triple-deck elevators, evacuation time with the specified elevators would decrease to about 15 minutes. Theoretically, it takes about three hours to evacuate the building on foot with meter-wide stairways. For a 15-minute evacuation time, 11-to-12 one-meter-wide stairways per floor were needed.

According to the simulation study, well-planned elevators provide a fast way to evacuate people if the emergency situation is detected at an early stage. At present, evacuation by elevators is not considered when planning elevators in tall buildings. According to current standards, elevators should not be used in a fire situation. There are, however, other less dramatic situations that may cause similar effects as simulated, e.g., down-peak before the lunch hour if one or two shuttle elevators are out of order. A simulation tool such as BTS helps to find critical bottlenecks of passenger traffic flow, and better and safer transportation arrangements can be suggested.

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**Marja-Liisa Siikonen** received her MSc in technical physics and the degrees of Licentiate of Technology and Doctor of Technology in applied mathematics from Helsinki University of Technology. She joined KONE Corp. in 1984 and currently works as manager of Traffic Planning in Helsinki, Finland.

**Tuomas Susi** is an undergraduate student at the Helsinki University of Technology. He is currently developing traffic simulation software in KONE Corp. and is working on his MSc thesis.

**Henri Hakonen** received his MSc in applied mathematics from the Helsinki University of Technology in 1996. He is a researcher in the Systems Analysis Laboratory at Helsinki University of Technology and is currently working on his PhD degree.