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**WORKING PAPER 10-02**

# MODELING INITIAL RESPONSE: FIREFIGHTER HIGH-RISE ACCESS TIME SIMULATION

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RACERS
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## About Christian Regenhard

Christian Michael Otto Regenhard was born on August 25, 1973. He was raised in Co-op City, Bronx, New York. After graduating from the Bronx High School of Science, he served five years in the United States Marine Corps, leaving as a decorated Recon Sergeant. He traveled extensively, often to remote areas of Central and South America, to pursue his love of rock climbing and diverse cultures. After studying language, art and writing at San Francisco State University, he was hired by the Fire Department of New York (FDNY), graduating from probationary school in July 2001. He was assigned to Ladder 131 when he was killed in the collapse of the World Trade Center on September 11, 2001 at age 28.

## About the Center

The Christian Regenhard Center for Emergency Response Studies (RaCERS) is an applied research center focused on development of a mix of grounded theory and traditional empirical analysis in the areas of emergency response, coordination of first responders, and dynamics of large-scale incident management and response. The Center is unique in its devotion to first responder-defined and actionable research on policy aspects of emergency response and homeland security from a perspective inclusive of police, fire, and emergency medical services.

## About the College

Since its founding in 1964, John Jay College of Criminal Justice has been a leader in the field of public safety, with a diverse variety of academic programs and research capabilities devoted to the study of emergencies and law enforcement organizations such as the fire service, police departments, emergency management offices, and security concerns unequaled by any other academic institution in the United States.

One of the unique aspects of John Jay is its student body. Our students represent a diverse mix reflecting New York, but also the nation and world. Our in-service students include many mid-career emergency responders from virtually every local, state, and federal law enforcement, security, and emergency response organization. As such, we have a unique and long-standing commitment to educating current and future leaders in the emergency response field. John Jay lost over 60 of its alumni, faculty, and students on 9/11. As such, we are uniquely dedicated to enhanced responder safety and effectiveness.

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# MODELING INITIAL RESPONSE:
# FIREFIGHTER HIGH-RISE ACCESS TIME SIMULATION*


## ABSTRACT

Historically, a high-rise building has been described as one which (1) was taller than the reach of fire service apparatus and, therefore, required interior firefighting, (2) posed the potential for significant stack effect (vertical interior smoke movement), and (3) required unreasonable time for occupant evacuation. High-rise buildings require firefighters to access the building and travel to an upper fire floor by using either stairs or elevators. The fire continues to grow during the time needed to apply water on the fire. This paper demonstrates ways for using Discrete Event Simulation (DES) to estimate the time for firefighters to access a fire floor using stairs. The results are compared to those produced by using DES to model the travel time to the same floor using elevators. One can develop a sense of proportion for comparisons of fire sizes at "first water" applications for the two different access methods.

The method used in this paper can be extended to analyze time duration to stretch hose lines for interior fire attack routes in any building layout. This type of analysis will give insight into the ways in which a building design can help or hinder interior fire suppression activities.


## INTRODUCTION

Although using elevators is desirable for the movement of firefighters and material, sometimes it will be necessary to use the building's stairs. Elevators can fail or malfunction during a fire. Till (2007) demonstrated that a fire attack evolution via stairwells in high-rise buildings can be modeled reliably using Discrete Event Simulation (DES). This paper uses DES to compare time differences for stair movement and elevator movement to staging areas at several levels in a hypothetical office tower. Fire sizes can be determined for these travel times to show the difference in conditions that may be expected at arrival at the staging area and application of "first water." For purposes of illustration, staging areas are located on floor levels 10, 20, 30 and 40, respectively.

High-rise fire fighting usually involves establishing a staging area one or two stories below the fire floor. This assures that the firefighters can operate in an area that will be relatively safe from smoke and heat and where supplies can be stored. For the purposes of this paper, staging areas are assumed to be set up on floors 10, 20, 30 and 40. The fire is assumed to be two floors above this staging area. The time needed to reach the staging area on each of these floors can be compared to fire growth during these different time durations. This analysis provides a sense of proportion for differences in fire size and the resources that may be needed in each of the scenarios.

## HIGH-RISE FIRES

High-rise fires can grow very quickly, particularly in offices with open floor plans. On May 4, 1988 the First Interstate Bank fire presented a high-rise fire challenge. The associated problems have been described from a fire safety engineering standpoint (including studies of heat release over time), as well as from a building system response position, and a review of the causes of the fire itself (Klem, 1988;

Nelson, 1989). A timeline for the growth of the fire compared to the fire department response is shown in Table 1.

Table 1: First Interstate Bank fire timeline

| Time | Time Elapsed | Event |
|---|---|---|
| 10:25(est.) | | Fire initiated on 12th floor |
| 10:38 | | A Category "B" assignment is dispatched (2 Task Forces, an Engine, a Squad and a Battalion) |
| 10:39 | 0 Min. | First engine company on scene |
| 11:43(est.) | 4 Min. | Fire department enters building |
| 10:51 | | 12th floor fully involved |
| 11:00 | 21 Min. | Fire suppression crews reach 12th floor (engines 9 and 3). Standpipes connected at floors 11 and 13. Inadequate water supply to continue (Pressure Release Valve adjusted). |
| 11:15 | 34 Min. | Engine companies 9 and 13 connect to standpipe in stairway 5 and advance on the fire floor. Floor fully involved at this time. |
| 11:23 | | Extension to 13th floor reported |
| 11:40 | | Extension to 14th floor reported |
| 12:39 | | Heavy fire on 15th floor, danger of spreading to 16th |

STAIR OPERATIONS

"The use of stairs to gain access to the upper floors of a high-rise building is not a very appealing option. Plain and simple, it means hard work. An average firefighter weights approximately 200 pounds. Add to that the personal protective equipment (PPE), self contained breathing apparatus (SCBA), hand tools, fire hose and spare air cylinders, and the firefighter quickly has 100 pounds or more of extra weight to carry. When we start talking about climbing stairs for distances of 20, 30 or 40 flights, the logistical portion of the high-rise operation rapidly becomes a very arduous and exhausting task. And don't forget, these firefighters have to fight a fire, search for occupants, and check for extension once they get to their destination" (McGrail, 2007).

Fire rated, enclosed stairs enable a fire department to operate inside a stairwell in relative safety for an interior fire attack. From this attack point, hose lines can be stretched and charged so that they are ready when the door to the fire floor is open.

ELEVATOR OPERATIONS

Firefighters are often reluctant to use elevators in high-rise fires because of unreliability and the potential of becoming trapped. Elevators were used initially at One Meridian Plaza in Philadelphia on February 23, 1991 (Routley, Jennings & Chubb, 1991). However, access was lost early in the fire due to a power failure in the building.

A small amount of water can stall an elevator to render it useless (McGrail, 2007). Power and mechanical failures can do the same. Firefighters trapped in a stalled elevator will need to be rescued themselves. If the elevator is above the fire this could be a critical problem. When utilizing an elevator equipped with fire service recall and control features, fire companies normally stop the elevator every several floors on the way to the staging destination in order to evaluate elevator performance. The following items are usually evaluated:

- Does the elevator stop at the desired floor?
- Do the elevator doors remain closed when the elevator stops?
- Do the elevator doors open when the door button is activated?
- Do the elevator doors close when the door open button is released before the doors are fully opened?
- Does the elevator car stop where the elevator car floor is level with the floor of the desired location?
- Does the elevator perform normally, and not in an erratic or potentially dangerous manner?

If the answer to any of these questions is no, switching to the stairs to gain access to the upper floors may be justified (McGrail, 2007).

## MODEL CONCEPT

DES is a general method that models real world processes which can be deconstructed into a set of logically separate tasks. In a DES model, each task in the process is assigned a duration, usually in the form of an appropriate statistical distribution. As the DES model is run, tasks are executed to represent a logical sequence of parallel or sequential activities. The result of each event is an accumulation of time durations and the ordering of all events to logically follow the completed activities. In this way, variations in time for all activities are combined to determine an overall process.

DES has the flexibility to address:

- Variations in the time required to perform individual tasks
- Tasks performed in sequence
- Tasks performed in parallel

Using DES for time duration studies of fire department evolutions enables "what-if" analyses to be performed to compare time durations for first water application. Combining the effect of architectural barriers that delay stretching attack lines with fire growth modeling provides a good picture of the influence of building design features and reliability on fire ground operations. Architectural obstacles are building features such as horizontal segments (doors, corridors, and directional turns for hose line placement), vertical segments (elevators and stairs), and decision delays (large rooms, clutter, and safety concerns) (Fitzgerald, 2004). In this paper, DES is used primarily to estimate vertical firefighter movement to a staging area and the fire floor.

## MODEL DEVELOPMENT

Models can account for both stair and elevator attacks. In this illustration, staging areas will be simulated on floors 10, 20, 30 and 40. The fire floors are assumed to be two stories above the staging area, and hose must be stretched from the staging area in both the stair attack and the elevator attack. For the purposes of this study, it is assumed that the office buildings are modeled with floor-to-floor distances of 12 feet. This assumption is important for both the elevator and stair access as it directly influences the distances firefighters will have to travel.

FIREFIGHTER STAIR EVOLUTION

The starting point for modeling fire attack movement using DES is the determination of the tasks that must be performed to stretch a hose line to the fire. The procedure models exterior and interior operations (tasks) of firefighters after they arrive at the scene. The tasks in a particular simulation depend on available equipment, staffing, and the tactics used. Standard operating procedures and how staffing is utilized can be included within these procedures. Thus, information about fire department equipment and tactics can be incorporated into an appropriate sequence of tasks. In addition, internal and external site information must be obtained so that delay from architectural obstacles can be incorporated into the model.

Data on task durations, descriptions, and sequences can be collected by video taping firefighter training evolutions, reviewing the tapes and identifying the individual tasks demonstrated (Till, 2001). Data obtained from the Australian Fire Brigade Intervention Model or any other appropriate source can also be used if the basis of the time durations is appropriate (Australasian Fire Authorities Council, 1997).

Selecting the proper statistical distribution for time durations to describe each task is important. Till (2001) identified a lognormal distribution as appropriate for the use in modeling of firefighter tasks based on videotaped data collected. Statistical distributions for each task were selected, and the Kolmogorov-Smirnoff (K-S) test was used to ensure that a lognormal distribution accurately and adequately described the task duration data. The Kolmogorov-Smirnov (K-S) is a goodness-of-fit test that is used to test whether a particular population conforms to a particular theoretical distribution (Ayyub & McCuen, 1997). An example fit is provided in Figure 2. In this case, the "Alight truck" distribution is described using a lognormal distribution developed as output from the Stat::Fit program (Geer Mountain Software Corporation, 1996).

- Alight Truck
- Don SCBA
- Remove Tool
- Proceed to Stairs (150m)
- Climb X Flights to Staging Area
- Rest Breaks (in the case of stair evolution)
- Climb 1 flight
- Connect hose to riser
- Climb 1 flight
- Set up hose in stair
- Rest or decision making break
- Connect Nozzle
- Charge Hose

Figure 1: Illustration of Tasks for an Evolution

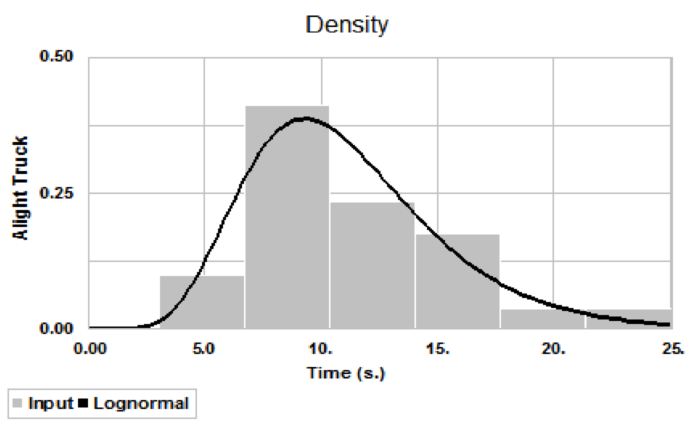


Figure 2: Lognormal distribution for "Alight Truck" Task

Data obtained from the Australian Fire Brigade Intervention Model was used to supplement the collected data. Although validation to the lognormal distributions described could not be performed on this data set, it was assumed that the distributions would also take the form of a lognormal distribution as developed by Till (2001). Eventually, the data and conditionality information must be coordinated to ensure compatibility.

Fatigue will be a factor in climbing many flights of stairs in tall buildings. Data on the influence of fatigue is not known. When the Australian data was collected, it was assumed that rest breaks were taken every 6 stories of stair climb and a distribution for these breaks was provided (Australasian Fire Authorities Council, 1997). This assumption was incorporated in the development of the results illustrated for this paper. The tasks described in the bulleted list were programmed into a GPSS/H model using the available distribution data (Banks, Carson, & Ngo Sy, 1995).

FIREFIGHTER ELEVATOR EVOLUTION

Data on emergency elevator operation is available and can be adapted to develop some of the information needed to determine when firefighters may be able to arrive on a fire floor (Klote & Alvord, 1992). Other information was made available by interviews of firefighters.

Clearly it is necessary to understand elevator speed, capacity, time durations and operation for the specific building of interest. A method devised by Klote and Alvord (1992) for developing times for the use of elevators for building evacuation was adapted for use in the model described in this paper. It was assumed that firefighters were operating on an elevator similar to the one described in Klote and Alvord's paper (1992). The elevator operation involves a period of constant acceleration, transitional acceleration, constant velocity, transitional deceleration and constant deceleration as shown in Figure 3.

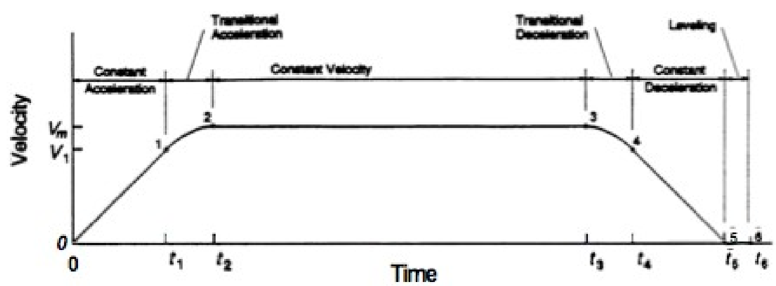


Figure 3: Elevator normal operating velocities (Klote & Alvord, 1992)

The method for determining the time for the elevator to arrive at the staging floor was also developed from Klote and Alford's model (1992). It assumes a maximum elevator speed of 600 f/s and an elevator acceleration of 4 ft/s$^2$. The model also assumes that the doors take 5.3 seconds to open and close. To address the issue of the elevator stopping during firefighter testing, it was assumed in all cases that the elevator was first stopped by the firefighters on the fifth floor before advancing to the staging floor. Therefore the "acceleration algorithm" was applied twice, once to get the elevator to the fifth floor, and again to get the elevator to the staging floor. A "leveling factor" of 0.5 seconds was also incorporated to address the issue of the elevator aligning with the proper floor. More frequent stopping can be incorporated if appropriate.

The initial inspection of the elevator shaft was assumed to take 45 +/- 15 seconds based on discussion with the Cambridge, Massachusetts Fire Department (O'Donoghue, 2010). A similar GPSS model to the stair attack was used with the representing the trip to the staging area.

RESULTS

The two basic models of stair and elevator operations were run for staging areas on floors 10, 20, 30 and 40. The results of the simulation are shown as a frequency distribution in Figure 4, which shows that elevator operations take on the order of 10 minutes regardless of the floor designated as the staging area.

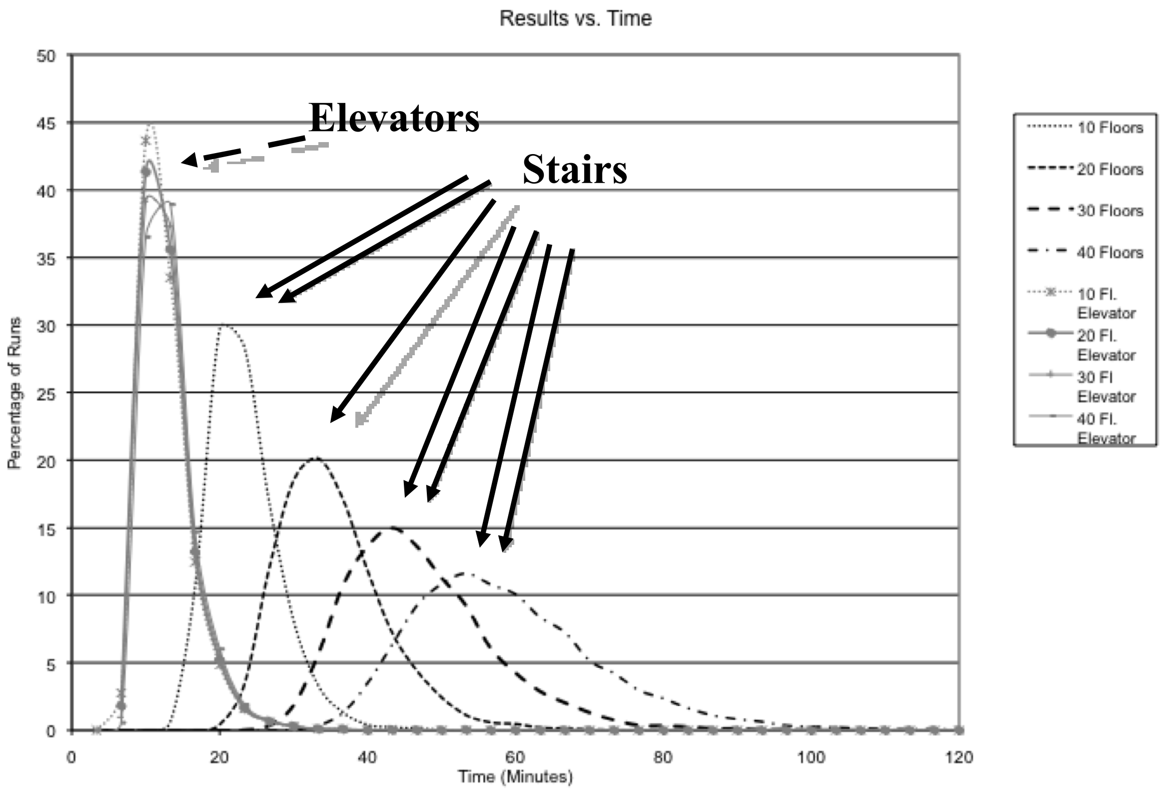

Figure 4: Overall results for the time to reach the fire floor

The mean results for the stair evolution are shown below. The tenth floor staging area results correspond well for reported intervention at the First Interstate Bank, which took 21 minutes. The simulations were run for 10,000 transactions.

Table 2: Overall results for stair evolution

| Staging Floor | Avg. Stair Access | Standard Deviation | Avg. Elevator Access | Standard Deviation |
|---|---|---|---|---|
| 10th | 21.7 Min. | 4.8 Min. | 11.1 Min. | 3.9 Min. |
| 20th | 33.5 Min. | 7.25 Min. | 11.3 Min. | 3.9 Min. |
| 30th | 45.4 Min. | 10.1 Min. | 11.5 Min. | 3.9 Min. |
| 40th | 57.3 Min. | 13.1 Min. | 11.7 Min. | 3.9 Min. |

The study of the response to the World Trade Center (WTC) collapse stated, "Generally a firefighter can climb a stairway at a rate of about 1 floor per minute" (Lawson & Vettori, 2005). This estimate corresponds well with the Table 3 results for average time in stairs for the first ten stories.

Table 3: Avg. Time in stairs to the staging area

| Staging Floor | Avg. Stair Access |
|---|---|
| 10th | 11.9 Min. |
| 20th | 23.7 Min. |
| 30th | 35.6 Min. |
| 40th | 47.5 Min. |

INFLUENCE OF FATIGUE

"Fatigue becomes a factor after approximately 12 floors of climbing, and fatigue caused by climbing diminishes the functional capabilities of the emergency responder to carry out operations once they reach the fire floor" (Lawson & Vettori, 2005). The WTC study included data for stair climbs higher than 12 stories, so it is assumed that these results would include fatigue. "Based on the data gathered, it is estimated that climbing rates varied between approximately 1.4 minutes per floor for personnel not carrying extra equipment to approximately 2.0 minutes per floor for personnel wearing firefighters' protective clothing and carrying extra equipment. These estimates have an error of +/- 0.5 minutes per floor" (Lawson & Vettori, 2005).

Based on the WTC estimates, and making a general assumption that the "one minute per flight assumption" holds until the 10th floor, the following generalized results can be assumed:

Table 4: In stair results with fatigue assumed after 10th floor

| Staging Floor | Minimum | Average | Maximum |
|---|---|---|---|
| 10th | 10 Min. | 10 Min. | 10 Min. |
| 20th | 25 Min. | 30 Min. | 35 Min. |
| 30th | 40 Min. | 50 Min. | 70 Min. |
| 40th | 55 Min. | 70 Min. | 85 Min. |

It can be seen that the minimum times making Lawson and Vettori's assumptions for in stair to staging areas correspond well with the average time in stairs developed within the GPSS simulation. The average and maximum times show what the influence of fatigue could be once the firefighters are operating on the upper floors.

COMPARISON WITH FIRE GROWTH ESTIMATES

When comparing the time for reaching the staging area and first water application, even without the potential for fatigue, it can be seen that the fire has a minimum of at least twice as long to develop in the case of stair access versus elevator access when the staging area is at the 10th floor. The First Interstate Bank timeline provided in Table 1 offers a sense of proportion of the situation, as the fire is located higher in the building. The potential for incorporation of fatigue makes the situation seem even more dire. Clearly there is a case for "fire hardened" elevators that may be less prone to failure due to water exposure, loss of power or other causes. The methods for fire hardening elevators are currently being studied by the ASME A17 Task Group on Use of Elevators by Firefighters.

## CONCLUSIONS AND DISCUSSION

A concept and procedure that can estimate time durations of movement for initial fire attack in stairwells and elevators in high-rise buildings has been described in this paper. The results of DES of high-rise firefighter intervention using stairs was compared with that using elevators for staging areas on floors 10, 20, 30 and 40. The results demonstrate that elevators show a distinct advantage over stairs in terms of time for firefighter access to these fires. That conclusion is, of course, obvious. Of greater importance is the recognition that a modeling tool exists that can realistically estimate the time durations for stretching interior hose lines in buildings. Although only stairs and elevators were used for this illustration, the tool can model any architectural layout. While necessary data have not yet been collected to develop field application estimates of time durations, DES provides a tool by which procedures can be developed to estimate time to first water application for any building with any local fire department. This becomes important during pre-incident planning in recognizing building features that help or impede interior fire fighting. It also enables one to have a consistent "yardstick" with which to grade the interior design and fire fighting equipment or other features in buildings.

While the results for this paper incorporated actual data with assumed and reconstructed information, the results are realistic when compared to the results of the First Interstate Bank fire. The principal goal of this paper is to create awareness that tools exist that can realistically model firefighting operations. These models can be very useful to evaluate the risk potential for different buildings and to compare alternatives for fire fighting operations of local fire departments. The methodology can also be extended to model other public safety interventions such as tactical law enforcement and emergency medical services.

## AUTHOR BIOGRAPHY

**ROBERT C. TILL** is an Associate Professor in the Department of Protection Management at John Jay College. He is involved in teaching and research in fire science. He received his PHD from Worcester Polytechnic Institute in 2001. His dissertation addressed the evaluation of buildings for fire department intervention using discrete event simulation. Robert is also a member of the ASME A17 Task Group on Use of Elevators by Firefighters and the National Fire Protection Association Standard for Fixed Guideway Transit and Passenger Rail Systems (NFPA 130) Committee. His email is <rctill@me.com>.

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