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# THE UK WTC 9/11 EVACUATION STUDY: AN OVERVIEW OF THE METHODOLOGIES EMPLOYED AND SOME ANALYSIS RELATING TO FATIGUE, STAIR TRAVEL SPEEDS AND OCCUPANT RESPONSE TIMES

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## ABSTRACT

This paper briefly describes the methodologies employed in the collection and storage of first-hand accounts of evacuation experiences derived from face-to-face interviews with evacuees from the World Trade Center (WTC) Twin Towers complex on 11 September 2001 and the development of the High-rise Evacuation Evaluation Database (HEED). The main focus of the paper is to present an overview of preliminary analysis of data derived from the evacuation of the North Tower.

## INTRODUCTION

The evacuation of the WTC complex on 9/11 is one of the largest full-scale evacuations of people in modern times with over 14,000 people escaping from the buildings. The survivors' evacuation experiences provide valuable insights into the factors that helped and hindered egress within the rapidly changing high-rise building environment. Thus understanding survivors' evacuation experiences is a vital component in unravelling the complex inter-related processes that drive high-rise building evacuation. Following 9/11 several projects were initiated around the world to study the evacuation of the WTC[1-3]. Project HEED[4-11] – High-rise Evacuation Evaluation Database - was a 3.5 year collaboration between the Universities of Greenwich (led by Prof Ed Galea who was also the project principal investigator, with team members, Ms Rachel Day, Dr Lynn Hulse, Mr Gary Sharp and Mr Asim Siddiqui), Ulster (led by Prof Jim Shields, with team members Dr Karen Boyce and Ms Louise Summerfield) and Liverpool (led by Prof David Canter, with team members Ms Melissa Marselle and Mr Paul Greenall) funded by the UK Engineering and Physical Science Research Council (EPSRC - project GR/S74201/01 and EP/D507790). As part of project HEED some 271 evacuees from the twin towers were interviewed generating almost 6,000 pages of transcript. While analysis of the data collected by project HEED is still underway, both by HEED project partners and independently by other researchers from around the world, including NIST in the USA, thus far the HEED team have produced 11 journal papers and conference presentations describing this work[4-11]. A full list of publications, including PDF versions of the publications can be found on the project web site at: http://fseg2.gre.ac.uk/HEED/. The main accomplishments of project HEED to date include:

- Developing and implementing an interview protocol capable of capturing the behavioural experiences of those who evacuated from the WTC twin towers;
- Developing an interactive on-line relational database (the HEED database) of the evacuees' experiences which includes full interview transcripts, allowing bona fide researchers and code officials access to the collected information;
- Undertaking preliminary analysis of the collected information to identify and quantify some of the key issues that influence building evacuation;

- Undertaking detailed analysis of the evacuation of the North Tower of the WTC through advanced computer simulation and using these findings to comment on the viability of full-building evacuation by stairs;
- The identification of current strengths and weaknesses in evacuation modelling technology and providing a basis for developing improved behavioural algorithms for high-rise building evacuation models.

The main features which distinguish project HEED from other WTC projects are:

- A more open approach to data collection through the development of an interview process that attempts to extract a richness of data not previously evident in other projects;
- An attempt to understand more fully the social and organisational factors that influence evacuation activity, e.g., the influence of groups, organisational structure and perception of risk;
- An attempt to quantify crowd densities and understand how these contributed to observed behaviour and human performance;
- Accessibility of the data, and full interview transcripts (almost 6,000 pages), through the development of an online relational database which is accessible by *bona fide* users. For example, amongst current organisations who have access to the HEED database is NIST.
- Detailed evacuation modelling analysis investigating a number of issues concerning the evacuation of the North Tower.

This paper will provide an overview of the methodologies developed for project HEED and provide a summary of some of the data analysis conducted by the FSEG HEED project team. A more detailed account of the research protocols can be found in[4].

## RESEARCH PROTOCOLS

The HEED project focused on those persons who evacuated from WTC1 or WTC2 on 9/11. Participants for the interviews were recruited mainly from the World Trade Center Health Registry (WTCHR), compiled by the NYC DOHMH. Individuals who wished to take part in the study were invited to register on the project's website and invited to complete a web based Pre-Interview Questionnaire. In total, 3,064 invitation letters were sent via the DOHMH. A 9.3% response rate was obtained from the DOHMH mailshot and 287 people registered to take part in our study. In total 271 interviews were conducted during five extended interview periods by the researchers in New York. The interview schedule comprised a combination of free-flow narrative and a semi-structured interview. Participants were asked to tell their story in their own words. The purpose of this was to enable participants to relax and facilitate memory recollection and uncover experiences and situations in the WTC evacuation that might not previously have been considered by the researchers. The free-flow narrative was followed by a semi-structured interview, during which the interviewer confirmed and expanded upon details previously provided in the free flow and sought to ascertain more specific information regarding the participant's entire experience relevant to the specific areas of research interest. Throughout the interview, interviewers attempted to extract from the participant as much contextual information relating to time and location of the described experiences. For example, it was considered important to determine an estimate for the actual time (absolute) that something occurred, and the time taken for certain events to occur, e.g., waiting in line, fire fighters to pass. Interviewers also attempted to establish where the participant was when this occurred (floor level, location on floor). Where absolute times could not be determined they tried to determine the times that things were occurring relative to global time markers, e.g., time WTC2 hit, time WTC2 collapsed. This information was crucial to address specific engineering research questions related to, e.g., response times, travel speeds, etc.

To quantify participants' experiences of crowd densities during the stair descent, computer generated animations of people descending stairs based on the classic Fruin densities (also often referred to as Level of Service or LoS)[12] were periodically administered. These animated images were introduced





whenever the participant entered or exited a stairwell, and whenever they mentioned crowding on the stairs. This information, together with information on time periods where important events occurred on stairs, assists in identifying travel speeds on stairs and associated crowd densities. During the interview, participants were also asked to complete risk perception and organisational structure questionnaires. The risk perception questionnaire comprised a general question on how at risk they felt at the time (rated on a seven point scale, from 1 'no risk' to 7 'very high risk') and why, followed by a series of statements related to different risk attributes, identified from risk perception studies, e.g., information available, control, dread, etc., to which they had to rate their level of agreement. Participants were asked to complete the risk perception questionnaire up to four different times during their evacuation, i.e. at WTC1 impact, when the participant was deciding to evacuate, when the participant knew that WTC2 had been hit (if applicable) and when the participant knew WTC2 had collapsed (if applicable). The semi-structured interview was piloted in New York over a period of six weeks. From the pilot study it became apparent that there were at least seven distinct phases that evacuees experienced during 9/11, namely: pre-recognition, recognition, response, horizontal evacuation, vertical evacuation, evacuation interruption (where participants chose to interrupt their evacuation, e.g., after the public announcements in WTC2) and exiting the WTC complex. These phases constitute a new model of evacuation behaviours and as such informed the development of the database.

## CODING PROCESS AND THE DEVELOPMENT OF THE HEED DATABASE

The HEED database is developed in Microsoft (MS) Access and is specifically designed to store and retrieve coded HEED WTC evacuation data from interview transcripts. The information stored in the HEED database provides a means to address key research questions relating to human factors issues associated with evacuation from high-rise buildings (see [4,7] for key research questions). The HEED database was developed from a content analysis of a small subset of participants' interview accounts. The content analysis indicated that participants' evacuations comprised of a variety of complex and detailed experiences ranging from observations and interpretations of events to subsequent feelings and actions. From the content analysis, a three level Experience structure was devised in order to systematically categorise participants' rich evacuation experiences into mutually exclusive categories. Data within HEED is stored using the logical arrangement of the three-level Experience hierarchy. In addition to coded Experience information, the HEED database also includes the full transcripts for each interviewed participant and the pre-interview questionnaire responses. The HEED database captures all of the participants' evacuation experiences such as stimuli (e.g., observational cues), cognitions (e.g., incident interpretations) and individual and group behaviours (e.g., actions and reactions) within the three-level Experience hierarchy. Supporting information such as the time of an experience and participant's location are captured by associated contextual information. The highest level of the hierarchy is the Experience Category or Level 1 experience. There are six core experience categories, namely: Action, Sensory, State, Cognition, Dialogue and Risk Perception. Below the Experience Category is the Experience Type or Level 2 experiences which identify the nature of the experience. The final element in the hierarchy is the actual Experience extracted from the text, also referred to as the Level 3 experience. The hierarchical experience structure can be thought of simply as short cut menus leading to the appropriate Level 3 experience[4].

In addition to coding the Level 3 Experience, 'contextual information' is required to clarify the detail of the experience. For example, the contextual information could be the time at which the experience occurred or an estimation of the crowd density when the experience occurred. As noted earlier, crowd density estimations are provided by the participant during the semi-structured component of the interview using a specially devised Fruin based tool. The time at which an experience occurred is represented within HEED in several ways. It can be actual or estimated times provided explicitly by the participant during the interview or a time interval estimated by the research team based on the evidence provided within the transcript. The time interval data coded in the HEED database consists of 14 specific time intervals and four specific key times. The time intervals are defined around the four key times, namely the impact into WTC1 at 8:47am (T1), the impact into WTC2 at 9:03am (T6), the collapse of WTC2 at 9:59am (T12) and the collapse of WTC1 at 10:28am (T18). As an example of this process, consider the time span between T1 and T6. This was divided into four sub-intervals with T3 being the sub-interval "Between T1 and T6" i.e. 08:47 < event time < 09:03, while sub-interval T2 is "Closer to T1 than T6" i.e. 08:47 < event time < 08:55. The first four time intervals (times in minutes measured from WTC1 impact) are, (0-8), (0-16), (8-16) and (15-16). The process of estimating the time when an event occurred involved the analyst reading the interview transcript and from the evidence provided determining which time sub-interval best captured the event time. Before the experience can be coded into the database it must first be identified. This is achieved by editing the interview transcripts into Behavioural Patterns (BP). BPs are chunks of transcript text which contain experience and corresponding contextual data. Once a BP is identified the relevant experience codes and contextual information relating to the experience are determined and coded into the database, along with the actual BP and its location within the transcript. A BP can have several mutually exclusive experience categories attached. As part of the data entry, the entire edited transcript of the interview is linked to the database, as is factual information obtained from the pre-interview questionnaire. Names of people and companies are removed from all entries, being replaced with coded IDs, ensuring that the identity of the participant remains confidential.

## DATA ANALYSIS

A vast amount of data was collected from the HEED interviews. In total 271 persons who evacuated the WTC on 9/11 were interviewed, 129 from the North Tower (WTC1) and 125 from the South Tower (WTC2), generating almost 6,000 pages of interview transcript. Analysis of this data will continue long after the formal end of project HEED. Here we present a portion of the data analysis conducted thus far by FSEG. Please note that the analysis presented here is the most recent analysis and contains more data then presented in an earlier publication[7]. Of the 271 people interviewed, 63.6% of the WTC1 population and 59.2% of the WTC2 population were males. The mean ages of the populations are 46 and 42.5 years of age for WTC1 and WTC2 respectively. The oldest person interviewed was 68 years of age (in both towers) while the youngest person interviewed was 24 and 22 years of age in WTC1 and WTC2 respectively. Of the population interviewed, 29% and 18% of the WTC1 and WTC2 population respectively had worked in the WTC towers for less than 12 months while 22% and 21% of the WTC1 and WTC2 populations respectively had experienced the 1993 bombing and evacuation. The majority of people interviewed were located in the upper third of the WTC1 and WTC2 i.e. 42% of the WTC1 sample and 57% of the WTC2 sample were located on floors above the 60$^{th}$ floor. The Body Mass Index (BMI) of the sample was also determined. The BMI is defined as the individual's body weight divided by the square of their height and is used to assess how much an individual's body weight departs from what is normal or desirable for a person of given height. For Western European and North American adults a BMI of: less than 17.5 may indicate anorexia; between 17.5 and 18.5 suggests the person is underweight; between 18.5 and 25 indicates optimal weight; between 25 and 30 suggests the person is overweight; between 30 and 40 the person is obese and over 40, the person is morbidly obese. For the WTC1 sample, 63% of the population was in the overweight/obese categories with 5% of the population in the morbidly obese category. For WTC2 population, 74% of the population was overweight/obese while 4% of the population was in the morbidly obese category. A total of 68% of the sample population were in the overweight/obese categories. Finally, the level of fitness of the participants was gauged from response to the questionnaire and was classed as being physically active or not. This in turn was based on National Health Service recommendations of engaging in 30 minutes of moderate intensity activity for five or more days per week. Some 64% of the WTC1 participants were not considered physically active based on this measure. In addition, 15% of the WTC1 sample were smokers and 24% had medical conditions that might affect their general fitness and/or mobility, e.g. respiratory problems, hypertension or arthritis.

### Frequency of Stops

The number of times evacuees stop during their descent is an important parameter as it will impact the average travel speed of the individual. The reason why evacuees stopped is also important as it





addresses issues associated with environmental conditions on the stairs and the possible contribution that the population demographic may have on occupant performance on the stairs. Several recent WTC studies[1,3] have reported lower than expected average stair travel speeds. Unfortunately, due to a lack of data in both these studies, it was not been possible to determine why the travel speeds were so low. There has been considerable discussion in the literature that the growing obesity epidemic[13] may be adversely affecting the ability of building occupants to travel large distances on stairs during building evacuations and may be the cause of the lower than expected average travel speeds found in these studies.

For these reasons stoppage data was extracted from the transcripts of 124 WTC1 participants (those evacuating from above floor 2). The data suggested that 85% (106) of the participants stopped at least once, and of these, 22% stopped once, 9% stopped twice, 2% reported stopping at least 20 times and 42% made an unspecified number of multiple stops during their descent. A total of 388 discrete stop incidents were reported by the participants. Congestion was the most frequent cause of stoppages, being reported by 58% of the population and causing 43% of the stoppages. The next most frequent cause of stoppages were caused by descending groups of people, often injured (17% of stoppages), or people ascending, typically fire fighters (16% of stoppages). In these situations the participants would interrupt their descent to allow the injured/fire fighters to pass. These types of incidents were reported by 33% and 39% of the population respectively. The third most common cause of stopping was fatigue - the need for someone, usually the participant's companion(s), to take a rest - with 8% of the reported stoppages due to this reason. Rest stops were reported by 17% of the population. The fourth most common cause of stoppages was due to environmental conditions. A total of 7% of the reported stoppages were caused by environmental conditions such as debris, smoke, heat, water on the stairs, etc. This type of stoppage was reported by 19% of the population. The stoppage frequency is summarised in Table 1. We note that at least 75% of the sample from each of the three floor regions reported stopping at least once however, participants in the High and Mid levels were more likely to stop during descent than those in the Low levels. This information relates to stoppages of all kinds and so does not distinguish between people requiring rest stops and those that stopped due to congestion or other issues. It is clear from this data that there were frequent interruptions to the steady descent of evacuees which would have contributed to the smaller than expected travel speeds. Also, it appears that the higher in the building the evacuee starts the evacuation, the greater the likelihood of stopping due to the greater chance of being subjected to the various stoppage reasons. In addition, over 90% of all reported stoppages were caused by reasons other than fatigue. Most participants did not feel the need to take rest stops. This applied even to people located in the upper part of the building and in the Overweight/Obese BMI category.

Table 1. Number of people requiring stops in WTC1

| Floor Region | No stops | Stopped at least once | Total |
|---|---|---|---|
| High: 61-90 | 7<br>13% | 47<br>87% | 54<br>100% |
| Mid: 31-60 | 5<br>11% | 41<br>89% | 46<br>100% |
| Low: 1-30 | 6<br>25% | 18<br>75% | 24<br>100% |
| Total | 18<br>15% | 106<br>85% | 124<br>100% |

For example, consider the following statement from a participant who started their evacuation from the 73$^{rd}$ floor with a BMI of 27 (Overweight):

**WTC1/073/0001, Page 22 L24-37**
I: Did you ever get tired yourself and have to stop and rest?
**P: Physically, no... I mean I encountered several people though that were experiencing difficulty getting out........ so there were people depending on your physical age and condition and whatever that struggled... I don't mean to make light of...**
I: No, no, it's okay.
**P: That it was "a walk in the park"... but me personally, I never felt physically challenged.....**

While this person started their evacuation from the upper third of the tower and was classed as "Overweight", he did not feel the need to take a rest stop. However, this person reported stopping two times due to congestion.

Table 2. Number of people requiring rest stops in WTC1

| Floor Region | No stops | At least 1 rest stop | 1 rest stop | 2 rest stops | 3 rest stops | 4 rest stops | Unspecified multiple stops | Total |
|---|---|---|---|---|---|---|---|---|
| **High 61-90** | 7<br>**35%** | **13**<br>**65%** | 8<br>40% | 2<br>10% | 0<br>0% | 1<br>5% | 2<br>10% | 20<br>100% |
| **Mid 31-60** | 5<br>**71%** | **2**<br>**29%** | 0<br>0% | 0<br>0% | 1<br>14% | 0<br>0% | 1<br>14% | 7<br>100% |
| **Low 1-30** | 6<br>**67%** | **3**<br>**33%** | 2<br>22% | 0<br>0% | 0<br>0% | 0<br>0% | 1<br>11% | 9<br>100% |
| **Total** | 18<br>**50%** | **18**<br>**50%** | 10<br>28% | 2<br>5% | 1<br>3% | 1<br>3% | 4<br>11% | 36<br>100% |

While few participants (only five) reported stopping specifically because they personally felt fatigued during their evacuation, there were cases where participants said they stopped because their companion(s) (18 reported, not interviewed) were fatigued. In the following analysis we compared data on people (participants and companions) who needed to stop and rest with data on the 18 participants who reported making no stops at all during their evacuation. Note, two companions were excluded as they were disabled, leaving a total sample of 39 individuals for rest stop analysis. Note also that as the companions were not interviewed, certain demographics (e.g. BMI score, floor they began evacuating from) was not directly available. However, participants' descriptions of their companions allowed for estimates (e.g. whether overweight/obese) to be made in many cases.

Approximately two thirds of the sample in the High region required rest stops while only a third or less of the sample in the Mid and Low regions required rest stops. Furthermore, approximately a quarter of the sample in the High and Mid region required multiple rest stops (see Table 2). With regards the people's physical characteristics, it is interesting to note that 85% of people who stopped and rested were female whereas only 50% of people not stopping were female, and that at least 62% of people resting had medical conditions while only 11% of the no stoppers did. The percentage of people stopping to rest who were overweight/obese (69%) was similar to that of people who did not stop during their evacuation (72%). This information suggests that BMI does not appear to be an indicator of whether a person was fatigued to the point that they required a rest stop. It should be noted that 65% of the WTC1 population surveyed were in the Overweight/Obese categories. The level of fitness of people who stopped due to fatigue versus those who did not stop was also considered. While the sample size was small and fitness information was missing in some cases, the individuals who stopped due to fatigue were, for the most part, no less fit than the individuals who did not stop during the descent – 60% of rest stoppers were not physically active compared with 67% of no stoppers. Thus BMI and level of fitness do not appear to be indicators of whether or not a rest stop is required.

However, when participants stop due to congestion, they were also resting. This is demonstrated by another participant who started on the 69th floor and had a BMI of 37 (Obese):





**WTC1/069/0001, Page 16 L21-27**
I: Did you ever stop to have a break to have a rest?
**P: Never no.**
I: Nothing like that.
**P: Only when I was forced, when it wasn't moving.**
I: When it wasn't moving, yes.
**P: Then I would sit on the step and I was watching and watching and someone would say okay we are moving now ....**

By default, participants forced to stop due to congestion or other external reasons were also resting and recovering. This may mask the effect of BMI in causing the participants to take a rest stop. To put the need to rest into perspective it is worth noting the total travel distances associated with descending from various levels within the WTC buildings. Using Stair C as the egress route and assuming that the central route down the stairs is taken, the total travel distance from 110th floor to the 2nd floor is estimated to be 1,439m; from the 90th floor, 1,192m; from the 60th floor 755m and from the 30th floor, 345m.

**Stair Travel Speeds**

Several WTC studies[1,3] have reported lower than expected average stair travel speeds. The UK BDAG study[3] first reported lower than expected travel speeds derived from their sample of survivor accounts published in the public domain. Their relatively small sample of useable data suggested a mean speed of 0.24 m/s. The later NIST report[1], based on a larger sample of first hand survivor accounts suggested an even lower mean travel speed of 0.2 m/s. To put these values into perspective it is worth noting the data reported by Fruin which is often used in engineering analysis[12]. Fruin measured free flow stair travel speeds of 700 males and females of various ages, both descending and ascending stairs. For males aged 30-50 descending stairs, his data produces a mean speed of 0.88 m/s (4.2 floors/min) while for males aged over 50 his data suggest a mean speed of 0.69 m/s (3.3 floors/min)[12]. In recent correspondence between Galea, Pauls and Fruin, it was noted that the free flow stair data measured by Fruin was over only one or two flights of stairs and so does not include the potential impact of fatigue on stair travel speeds[14]. As a result, Galea suggests that this data should be used with care in high-rise building applications. Other data often quoted concerning stair travel speeds is derived from observations of high-rise building evacuation drills which suggests a mean speed of 0.52 m/s (2.5 floors/min) in optimal flow conditions and 0.22 m/s (1.1 floors/min) in crush conditions[15]. As a reference, it is worth noting that for Stair C of the WTC a speed of 1.0 floors/min is equivalent to 0.21 m/s while 3 floors/min is equivalent to 0.62 m/s. Estimating the stair travel speed from participant transcripts is a difficult and time consuming process. Thus far we have restricted our analysis only to people who completed their journey from start to finish on a single stair. Analysis is further restricted to individuals for which we have a reasonable estimate of when they entered the stairs and when they left the stair. An individual's journey between the beginning and end points is reconstructed from information provided in the interview transcript, noting events such as:

- Environmental conditions encountered – where and when?
- Encountering fire fighters – where, when, how long?
- Encountering injured being carried down – where, when, how long?
- Encountering congestion – where, when, how long, Fruin Density?

In reconstructing segments of the journey it is often necessary to make some assumptions concerning aspects of that part of journey e.g. duration of stoppage if not provided. In addition, sometimes it is necessary to estimate the speed in terms of floors/min based on the provided Fruin density and description of movement e.g. if Fruin F estimated and participant describes very slow movement, we assume approximate speed of 1 floor/min – unless other evidence is provided to suggest a faster speed. Where it is not possible to make reasonable estimates of journey segments, a simple average speed is determined for the journey from beginning to end. The following extract from an account demonstrates an estimation made by the participant of the crowd density (Fruin Density F = Orange) at floor 55, how he travelled very fast down the stairs from floor 60 to 55 and then come to a stop when encountering the Fruin F.

**WTC1/060/0001 P11 L24-40**

I: Okay, so that's Orange. And so when it got congested, did you say this was because other people were coming into the stairs?

**P: Yes, other people were coming in as well as already in the stairwell from whatever floor they had come from.**

.........

I: And how did that affect the travel speed?

**P: It slowed down dramatically.**

I: So, were you having to stop at any point?

**P: We stopped at 55, right there, because there was obviously a lot more people. I mean we were running down for the first 5 stairs, "Boom, boom, boom, boom, boom", two stairs at a time sometimes. When we got to 55, we couldn't do that because we would plough into people ....**

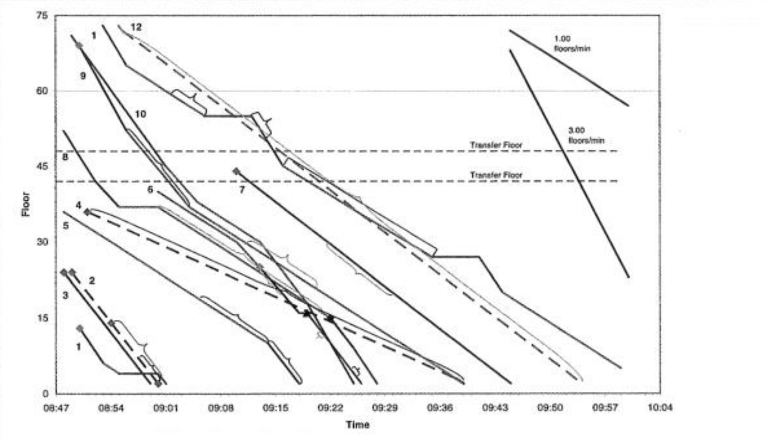


Figure 1. Floor vs time diagram for 12 evacuees using Stair C

Using this type of information it is possible to construct a "Floor–Time" diagram for the participant. The diagram provides a very useful way of visualising the progressive evacuation of a high-rise building. When used forensically in reconstructing an evacuation based on first hand survivor accounts, it also provides a means of corroborating the accounts of the evacuees, checking the consistency of assumptions in reconstructing the path and filling in information gaps in the accounts of some evacuees. Depicted in Figure 1 is a Floor-Time diagram for 12 evacuees who used Stair C that meet the criteria described above. The numbers on the curves indicate the participant ID, e.g. 2 refers to participant WTC1/021/0001 (BMI 18.6) who started their evacuation on the 21st floor. The slope of the line or line segment represents the speed of the participant in floors/min. For participants 2 and 12 the average travel speeds are 2.0 floors/min and 1.2 floors/min respectively. These speeds can be converted to an approximate speed in m/s using the approximate 12.3 m travel distance estimate or a more accurate conversion can be derived using the actual travel distance for the floors covered, including transfer corridors, the latter is used here where possible. There are several innovations to the standard Floor-Time diagram that have been introduced in this project to convey additional information relating to the descent of the individuals. Each line segment is coloured according to the Fruin density that was reported by the individual. Black indicates that no Fruin density was reported,





Blue indicates Fruin densities of A (< 0.5 p/m$^2$) or B (0.5 – 0.7 p/m$^2$), Green indicates Fruin densities of C (0.7 – 1.1 p/m$^2$) or D (1.1 – 1.4 p/m$^2$) and Red indicates Fruin densities of E (1.4 – 2.5 p/m$^2$) or F (> 2.5 p/m$^2$). Coloured squares indicate a spot Fruin density only at the specified location. A dashed line indicates that there were complications along the egress route that makes the path unrepresentative of the travel speeds that one would normally expect, even for the level of congestion encountered. For example, participant 2 suffered from a serious pre-incident medical condition which made their travel speed unrepresentative while participant 4 reported stopping 10-20 times during the descent and participant 12 was reluctant to overtake the people in front of him who were carrying a disabled person down the stairs.

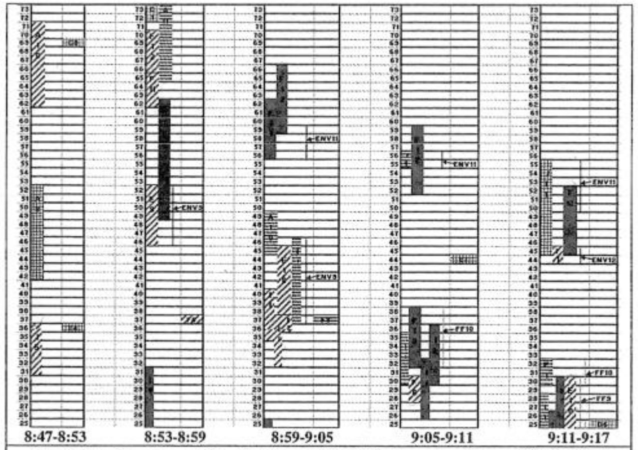


Fig. 2. Fruin map of North Tower Stair C showing floors 25-73 in 6 minute time slices up to 9:17

Various types of brackets are also shown along some of the journey segments. These are used to represent the presence of factors which may impact the travel speed. A curved bracket indicates that the factor occurred somewhere in the region indicated but a precise location was not provided while a square bracket indicates that the factor persisted over the entire region indicated. The colour of the bracket also carries some significance. Gold indicates the presence of fire fighters ascending the stair which interfered with the participants downward progress, Red indicates a Fruin density of E or F and Black indicates the presence of environmental factors such as smoke, heat, dust, water or debris which impacted the progress of the participant. For complicated paths such as 1 or 11 a travel speed can be determined for each segment of the journey and an overall average speed can be determined by simply taking the beginning and end points. For participant 1 the average travel speed for the journey from floor 13 to floor 2 is 1.0 floors/min (0.21 m/s) while for participant 11 the average travel speed from floor 73 is 1.03 floors/min (0.22m/s). Note that both these participants have periods during their journey where they have passed through high crowd density regions (Fruins E and F) and participant 11 has stopped his journey on two occasions. As can be seen from Figure 1, when the participant passes through high crowd density regions their travel speed, measured by the slope of the line, is less than when they travel through lower crowd density regions. Using the Floor-Time diagram we thus note that at times participant travel speeds can be considerably higher than suggested by taking the simple average travel speed. Furthermore, we can also measure the impact that the stoppages and high crowd densities can have on the average travel speed. This may begin to explain why the early BDAG[3] and NIST[1] studies found lower than expected travel speeds.

Using the information provided by the interview transcripts it is possible to construct a Fruin Map of the WTC buildings. The Fruin map provides an indication of the crowd densities on the stairs as reported by the survivors. In addition, information relating to the environmental conditions on the stairs and the location and time at which fire fighters were encountered can also be recorded. The Fruin map displays each floor in the tower and indicates the conditions on the stairs in small time slices. Presented in Fig. 2 is an example of a portion of the Fruin Map for Stair C showing floors 25-73 in 6 minute time slices. Each entry in the Fruin Map is derived from a survivor statement. The coloured bars represent the Fruin density as described for Figure 1. In addition, the coloured bars are numbered so that the particular statement can be found (numbering same as used in Figure 1) and the coloured bar also carries the actual Fruin density. The coloured entries that cover only a single floor represent the Fruin density estimates provided by the participants on entry into the staircase. As the time slices used in the Fruin map are of finite duration, the crowd density observation provided by the evacuee may not cover the entire duration of the imposed time slice. To reflect this, a fill pattern has been introduced that describes the portion of the time slice that the observation is valid for. A solid fill suggests that the observation is valid for the entire duration of the time slice. A hash fill indicates that the observation starts after, and ends before the time slice. Horizontal bars indicate that the observation ends before the specified time period while diagonal bars indicate that the observation starts after the beginning of the specified time period. Using this system many of the apparent conflicts in crowd density may be explained. In addition, vertical gold lines indicate the presence of fire fighters while vertical black lines indicate adverse environmental conditions were encountered.

Table 3. Travel speed and percentage of journey subjected to various crowd densities for Stair C

| ID WTC1 | Graph ID | BMI | Physically Active | Unknown Fruins | Low Fruins (A,B) | High Fruins (E,F) | Original Average Speed (m/s) | Average Adjusted Speed (m/s) |
|---|---|---|---|---|---|---|---|---|
| 13/0002 | 1 | 28 | No | 50% | 25% | 25% | 0.21 | 0.38 |
| 21/0001 | 2 | 19 | Yes | 87% | -- | 13% | 0.41 | 0.41 |
| 24/0001 | 3 | 26 | Yes | 96% | -- | 4% | 0.41 | 0.41 |
| 36/0002 | 4 | 28 | Yes | 91% | -- | 3% | 0.15 | 0.15 |
| 36/0003 | 5 | 48 | No | 23% | -- | 77% | 0.23 | 0.23 |
| 40/0001 | 6 | 24 | No | 0% | 38% | 64% | 0.30 | 0.31 |
| 44/0002 | 7 | 37 | No | 98% | -- | 2% | 0.25 | 0.25 |
| 52/0004 | 8 | 25 | No | 10% | 49% | 45% | 0.27 | 0.31 |
| 69/0001 | 9 | 37 | No | 0% | 24% | 75% | 0.29 | 0.29 |
| 71/0004 | 10 | 26 | No | 0% | 63% | 40% | 0.41 | 0.41 |
| 73/0001 | 11 | 27 | Yes | 0% | 41% | 68% | 0.22 | 0.27 |
| 73/0003 | 12 | 33 | Yes | 96% | -- | 1% | 0.26 | 0.26 |

The Fruin map can be used in conjunction with the Floor-Time diagram to fill in gaps in the Fruin density information provided by some of the participants. This enables a better understanding of the environment through which the participants travelled. Putting all this information together provides a possible explanation for the apparently low average travel speeds observed. Firstly, the travel speeds of four individuals (1,6,8,11) can be adjusted upwards by taking into account the identified stops. Secondly, two individuals (4,12) had low travel speeds due to complicating factors i.e. one was travelling behind a group carrying a disabled individual and did not wish to overtake (12), while the other person had pre-existing medical conditions which effectively meant that he had a movement related disability (4). Using this sample of 10 people produces (see Table 3) an average stair speed of 0.33 m/s for occupants on Stair C. A similar analysis was completed for Stair A and B which produced average stair speeds of 0.25 m/s derived from 13 occupants on Stair B and 0.31 m/s derived from seven occupants on Stair C. Using the results from all 30 occupants produces an average stair





travel speed of 0.29 m/s. While this speed is 45% larger than the average reported in the NIST study[1] it is still relatively low. Further analysis of the travel speed data reveals that those individuals with average travel speeds lower than the group mean speed experienced high crowd densities for at least 60% of their journey (see Table 3 for Stair C), with the lowest calculated average travel speed of 0.17 m/s (ID, 49/0001, Stair B) corresponding to an individual that spent 94% of their journey in high crowd densities. While those with average travel speeds higher than the group mean travel speed spend only short parts of their journey in high crowd densities. We can also consider average travel speed as a function of BMI. The average speed for the various BMI categories are: optimal, 0.29 m/s (10 individuals); overweight, 0.28 m/s (14 individuals); obese, 0.29 m/s (3 individuals) and morbid, 0.28 m/s (2 individuals). For users of Stair C for which we have travel speed data (10), 42% (4) of the sample were considered to be fit. Taken across all three stairs, for the users for which we have travel speed data (30), 40% (12) of the sample were considered fit. We find no correlation between travel speed and fitness. These results suggest that BMI and fitness is not a predictor of stair travel speed and that the low average stair speed observed for participants may simply be due to the relatively high crowd densities encountered during the descent. However, the impact of crowd density may mask the effect of BMI and fitness.

**Response Times**

The occupant response times coded into the HEED database proved too course to allow meaningful analysis of response times for WTC1. As a result, the FSEG team defined four additional time intervals (18 time intervals and 4 key times) and recoded the response time data as described above. As a result, the response times for WTC1 were coded into one of 10 time bands (measured in minutes from WTC1 impact), namely: **(0-1), (1-4)**, (1-8), (1-16), (8-16), **(12-16), (16-21)**, (16-26), (16-72), (44-72). A total of 119 response times were derived from the transcripts. Due to small samples within the above time bands, data was further collapsed into three broad response time groups i.e. Rapid (< 1 min), Moderate (> 1 and < 8 min) and Long (> 8 min) and the vertical spatial distribution of the building was split into three broad categories Low, Mid and High as shown in Table 4.

Table 4: Response time distribution for WTC1

| Region | Rapid < 1 min | Moderate 1 – 8 min | Long > 8 min | Total |
|---|---|---|---|---|
| High: 61-90 | 8% (4) | 86% (43) | 6% (3) | 50 (42%) |
| Mid: 31-60 | 16% (7) | 71% (32) | 13% (6) | 45 (38%) |
| Low: 1-30 | 17% (4) | 75% (18) | 8% (2) | 24 (20%) |
| Total | 13% (15) | 78% (93) | 9% (11) | 119 |

From Table 4 we note that within each floor group, over 70% have Moderate response times and overall almost 80% of the population have Moderate response times. In addition, the High region has the largest Moderate response time group and the smallest groups with Rapid and Long response times. The relative low numbers of rapid responders high in the building is thought to be due to the relative proximity to the incident, with the population in this part of the building experiencing the most severe physical effects resulting from the impact and as a result not being able to react as quickly as people elsewhere in the building. Similarly, this region has the lowest number of Long responders. Again, having experienced the most severe physical affects of the impact, this group was less likely to delay their evacuation.

In addition to the time taken to react, the nature of the tasks undertaken during the response phase was examined. Two types of task were considered, **Information Seeking** and **Action** Tasks. The **Information Seeking** tasks involve participants attempting to gather information prior to commencing their evacuation. Examples include; Sought environmental information; sought information from colleagues, authority figures, etc; waited for further info; etc. **Action** tasks involve performing physical actions prior to the commencing horizontal evacuation. Examples include; Collect items; searched office/floor; instructed others to evacuate; shut down computer; secured items (locked safe); changed footwear; etc. A total of 469 tasks were completed by 119 participants, 175 **Information**

Seeking Tasks and 294 **Action Tasks**. It should be noted that a number of participants completed the same type of task more than once. A positive significant relationship was found between total number of tasks completed and response time $\tau$=.51, p (one tailed) <0.01, i.e. the more tasks completed the longer the response time. On average a person completes 4 tasks (1.5 **Information** and 2.5 **Action Tasks**) prior to starting to evacuate. Half the population (50.4%) undertake three or less tasks in total prior to entering the stairs. In addition, four fifths (59.7%) of the population undertake up to two **Action Tasks** while four fifths (60.5%) of the population undertake up to one **Information Seeking Task**. The two most common **Information Seeking Tasks** were, "Sought environmental information", reported 64 times (37% of all Information Seeking Tasks) and, "Sought information from friends/colleagues", reported 44 times (25% of all Information Seeking Tasks). The two most common **Action Tasks** were, "Collect Items", reported 143 times (49% of all Action Tasks) and "Instructed Others to evacuate", reported 52 times (18% of all Action Tasks).

Clearly, participants undertake a number of tasks prior to starting their evacuation. As it was not possible to determine a unique response time for each of the participants the upper end of the response time band associated with each participant was used to represent the maximum likely response time for an individual undertaking a particular set of tasks. Using this information it is possible to estimate the response times associated with undertaking those tasks (see Table 5). We note that starting the evacuation without undertaking any tasks results in the shortest average maximum response time, requiring only 1.8 mins. This is an indication of the minimum time required by an individual to start their evacuation in this type of incident. It represents the time required to overcome the initial disorientation created by the incident, decide to evacuate and begin to purposely move towards the exit stairs. Removing this time from the response times for undertaking various numbers of tasks provides an indication of the average time required to undertake these tasks. Applying this to the data presented in Table 5 suggests that the average time to undertake an **Information Seeking Task** is 3.2 min while the average time to undertake an **Action Task** is 2.0 min. Thus the time required to undertake an **Information Seeking Task** is some 1.6x longer than the average time to undertake an **Action Task**. Of interest is the result that **Information Seeking Tasks** appear to take longer on average than **Action Tasks**. It is suggested that the frequency and number of **Information Seeking Tasks** could be reduced or removed completely if appropriate information could be provided to evacuees via hardened buildings communication systems. Furthermore, it is suggested that the frequency and number of **Action Tasks** could be reduced or removed completely if appropriate training and clear instructions are provided to building occupants.

Table 5: Average maximum response time associated with various task types

| Type of Tasks "0 Action and" | Average Max Response Time (mins) | Sample Size | Type of Tasks "0 Info and" | Average Max Response Time (mins) | Sample Size |
|---|---|---|---|---|---|
| 0 Info | 1.8 | 11 | 0 Action | 1.8 | 11 |
| 1 Info | 4.0 | 5 | 1 Action | 2.9 | 11 |
| 2 Info | 4.0 | 3 | 2 Action | 4.0 | 6 |
| 3 Info | 6.0 | 2 | 3 Action | 4.0 | 2 |

Finally, the perceived risk when the participant decided to evacuate (R2) was compared with their maximum response time. This could be done for 91 participants for which we have a (R2) risk and a maximum response time. Participants with Low Perceived Risk (rating 1,2) have the highest average maximum response time of 6.7 mins (13 individuals) while those with High Perceived Risk (rating 6,7) have the shortest average maximum response time of 5.3 mins (30 individuals). Thus those who perceive a high risk respond 1.26 X faster than those who perceive a low risk.



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## CONCLUDING COMMENTS

As part of the UK study into the WTC evacuation, 271 WTC survivors have been interviewed in great detail and data from these interviews have been entered into the HEED database. The main findings from the analysis of the WTC HEED data suggest:

**Stoppages:**

- From a sample of 124 people in the North Tower (WTC1):
  - 85% of the sample, stopped at least once during their descent in 388 stop incidents.
  - 43% of stoppages were due to congestion while 8% of stoppages were for rest.
  - At least 87% of sample in the Mid and High levels stopped at least once, compared with 75% from low level.
  - 72% of rest stops were incurred by those in the High region.
  - Rest stoppers were: 85% female, 69% overweight+, 62% with medical conditions.
- BMI and fitness are not predictors of whether a person required a rest stop however; effects may be masked by other types of stoppages providing rest opportunities.

**Stair Travel Speeds:**

- Analysis of travel speed data for 30 occupants suggests an average adjusted stair speed of 0.29 m/s, some 45% larger than reported in earlier studies.
- Occupants with stair speeds less than the average speed encountered high levels of congestion for at least 60% of their journey. The lowest recorded speed of 0.17 m/s resulted from an occupant on the 49$^{th}$ floor who encountered high levels of congestion for 94% of their journey.
- It appears reasonable to suggest that the lower than expected stair speeds appear to be affected predominately by high levels of congestion experienced on the stairs for significant periods of time.
- BMI and fitness are not predictors of stair travel speed however; effects may be masked by high levels of congestion encountered.

**Response Times:**

- Response times for 119 people from the North Tower (WTC1) have been estimated.
- Almost 80% of the sample have moderate response times (1-8 min).
- The High Region (> 60$^{th}$ floor) has the smallest number group of Rapid (<1 min) and Long (>8 min) responders – this is thought to be due to proximity to event.
- On average a person completed 4 tasks prior to starting to purposefully evacuate.
- Half the population undertake three or less tasks prior to evacuating while 9% undertake no tasks.
- Four fifths of the population undertake up to two **Action Tasks** while four fifths of the population undertake up to one **Information Seeking Task.**
- On average an **Action Task** required 2 min and **Information Seeking Tasks** take 1.6x as long as **Action Tasks.**
- Improving emergency communications could greatly reduce evacuation delays by removing the need to perform **Information Seeking tasks.**
- Improving training could reduce evacuation delays by removing the number of **Action tasks** prior to evacuation.
- Those with a High Perceived Risk responded 1.26x faster than those with Low Perceived Risk.

An important observation to emerge from this study is that BMI and fitness do not appear to be predictors of the need to rest or of stair travel speed. It is believed that high levels of congestion contributed to the low average travel speeds observed in this incident. However, the impact of BMI and fitness may be masked by the high levels of congestion.

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