Five Grand Challenges in Pedestrian and Evacuation Dynamics

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Abstract This paper identifies five grand challenges in the multidisciplinary field of pedestrian and evacuation dynamics (PED). In order to maximize the effectiveness of limited resources, the PED community would benefit greatly from a prioritized, consensus-based research agenda. The five proposed research initiatives include (1) a general human behavior model with a theoretical foundation and numerical validity, (2) a database archiving actual building emergency evacuations, (3) methods to embrace the stochastic nature of inputs and outcomes in building evacuation, (4) a validated method to integrate distributions of egress calculations with fire hazard calculations, and (5) adoption of technology for people movement, data collection, and within modeling constructs. The list proffered in this paper is intended merely as a spark for discussion amongst the greater PED community; a true consensus research agenda requires deliberation by leaders in the community.

Problem

The emerging field of pedestrian and evacuation dynamics (PED) has the potential for tremendous impact on the built environment by achieving design elements which are safe, intuitive to use, and support the intended purpose of the structure or space. However, resources historically committed to PED research have limited progress in the science and simulation of PED. These resource limitations manifest in two primary ways: the geographic and disciplinary distribution and the magnitude of research infrastructure.

First, the research and implementation efforts are widely distributed. Note that these phenomena would be expected in an emerging discipline. With a few notable exceptions, progress is led by individuals at geographically diverse institutions and originates from diverse disciplinary backgrounds, both of which serve as obstacles to collaborative progress. Regular symposia such as the PED meetings, along with digital networking and productivity tools, minimize the geographic distribution problem. However, disciplinary diversity, while bringing novel approaches and perspectives to PED, can also lead to confused terminology, anchoring around pre-existing physical or theoretical analogies, and competing goal structures.

Second, the PED community has limited resources relative to the magnitude of the problem. Careless or unknowing building and space design can create confusion, inefficiency, and safety concerns for users. On the other hand, the potential for positive impact is substantial. Well-designed buildings and spaces ensure safety during emergency situations, enable efficient and intuitive circulation, and promote the functions of the space (mercantile spaces promote commerce, museums promote art viewing, and mass transit stations enable a high throughput of objective-based movement, for example). Satisfying these disparate objectives, however, requires a fundamental understanding of human behavior, cultural and social norms, crowd dynamics, interaction of people with the built environment, human factors of technology interfaces, and human physiology. Prediction and analysis of people movement requires mathematical, statistical, and graphical sophistication. The current state of PED practice generally lacks a grounded theory, employs a limited number of data sets, and often fails to capture the stochastic nature of both the inputs and outputs of models. Despite the numerous research opportunities in this field, there are perhaps a few hundred researchers and practitioners actively engaged in advancing the science and theory of PED. Only a handful of academic institutions support curricula oriented towards PED science and simulation. As a result of these resource limitations, progress is slower than would be expected given the potential for positive societal impact.

Therefore, in the context of these structural barriers to progress, the PED community would benefit greatly from a prioritized, consensus-based research agenda. By marshalling limited resources towards collectively or systematically addressing significant issues, the field can mature more rapidly and maximize the impact of future efforts. A consensus research agenda approach has been successful in other disciplines at guiding both researchers during the proposal development stage, as well as agencies or organizations which fund research. If a research proposal has the magnitude of the problem validated by an objective, traceable publication linked to the consensus of disciplinary experts, confidence in successful outcomes is increased in both funding and receiving parties. One example of a successful consensus research agenda is the Firefighter Life Safety Initiatives [1]. A representative cross-section of fire service leaders gathered and achieved consensus on sixteen priority research needs. The document subsequently guided grant applications and awards from agencies of the U.S. Federal Government. A second example of a research agenda includes the six research priorities identified in "Grand Challenges for Disaster Reduction [2]," a document developed by the U.S. National Science and Technology Council's Subcommittee on Disaster Research.

The purpose of this paper is to suggest five grand challenges which impede quantum progress in the PED field as a prompt for further discussion within our community. The scope we have used in this effort is that each of the challenges described herein must be addressable within the next ten years, given appropriate resources and, once solved, the solution must enable significant progress in the field. While this list is not comprehensive or complete, the purpose is to engender spirited discussion about necessary research priorities, along with what steps, metrics, and resources will be required for making progress. Other significant challenges in the PED community warrant research and a true consensus research agenda requires deliberation by leaders in the community.

Grand Challenge #1: Develop and validate a comprehensive theory which predicts human behavior during pedestrian or evacuation movement

While there are dozens of predictive computer models for people movement and building evacuation [3], physics-based and other movement models are inadequate to predict the full range of possibilities for pedestrian and evacuation scenarios. The pre-evacuation actions of occupants can account for a significant portion of the overall building evacuation time. Specific actions can be a function of many factors, including situation awareness, cue interpretation, prior experience, risk perception, and social context. There are three steps necessary to achieve a full accounting of human behavior in computational models: development of grounded theory, development of methods to collect behavioral data, and development on computational methods to implement the results of the first two steps.

The first step will be to develop and validate theoretical behavioral models, several variants of which already exist [4]. Kuligowski [5] reviewed the state-of-the-art in modeling of human behavior during building evacuation and proposed a general process model for occupant response to physical and social cues during emergency evacuation. Furthermore, the lack of a general theory of human behavior grounded in the science of psychology and sociology, results in two difficulties. First, experimental designs for data collection (observational or interrogatory) may lack the structure of being guided by theory. As a result, the design may lack completeness (specification error). Second, data analysis may be reduced to haphazard association or correlation of factors without understanding of causality or incorporation of statistical controls for other important factors.

Once a general theory is developed (or proposed), methods (beyond observational) should be developed which can validate the whole of or components of the theoretical behavioral models. However, in order to collect the data, research should extend the current methods to account for the myriad of complex factors which determine behaviors. Examples include expressed versus revealed preference, identification of unconscious motivations, and the variance in individual situation awareness, all of which affects the selection of data collection methods and validity.

The final step is to integrate the theoretical models into the pedestrian and evacuation computational models. Behavior, like individual walking speeds, is unique to an individual and must be accounted for with stochastic approaches. The subsequent grand challenge ("#3: Embrace variance") contains a more complete discussion of the difficulties of incorporating these phenomena into computational models.

Grand Challenge #2: Create a comprehensive database of actual emergency data

The field of pedestrian and evacuation dynamics has developed largely on the foundation of a small number of data sets (primarily Predtechenskii and Milinskii [6], Fruin [7], Jin [8], and Pauls [9]). The foundational data are generally over 30 years old and are routinely extrapolated beyond the scope of the collection. A primary example of extrapolation is the application of pedestrian movement data or non-emergency evacuation data to emergency scenarios. Such extrapolation is necessary in the absence of a comprehensive set of emergency evacuation data. Several differences exist between non-emergency and emergency evacuations, possibly including:

- perception of imminent danger to self or others,
- visibility of evacuation path due to smoke, loss of lighting, or other event,
- blockage of escape routes due to heat, debris, or other event,
- full participation by all occupants, and
- knowledge that the building may not be reoccupied may encourage additional gathering of items (keys, purses, computers, phones, jackets, etc).

These differences may have the effect of lessening the building evacuation time or lengthening the building evacuation time, dependent upon the specific scenario. Currently, however, scant information exists which examines the applicability of the existing data for real emergency scenarios. In other words, there is an unknown mapping between fire drill or experimental data and real emergency scenarios. A comprehensive database which catalogues the progress and outcomes for real emergency incidents (the crucible in which theory and drills are tested) is necessary condition for acceptance and validation of all knowledge in the field.

Presently, buildings with emergencies are black boxes, wrapped in a myriad of technical and bureaucratic obstacles. First, building evacuations involving injuries or deaths are often complicated by civil and criminal proceedings which may inhibit access to critical data. Data records may include security video, emergency responder radio communications, interviews with building staff and evacuees, or emergency planning records. Second, even if the researchers knew when and where an event would occur, the infrastructure to collect, analyze, and archive the data consistently across incidents has not yet been developed. Finally, reconstructions are resource intensive, requiring substantial labor and funding resources to properly document large events.

Gwynne [10], [11] has documented many of the challenges which impede progress in the collection of egress data. Gwynne has proposed a new framework which begins to address many of these challenges, including (1) standardized vocabulary within the egress community, (2) identification of the context and purpose of the evacuation, (3) characterization of the building and occupants prior to the building evacuation, (4) archival of raw data (across multiple formats such as spreadsheet and video), and (5) linkage of data to analyses or conclusions produced in published works. Galea has also produced databases for archiving aircraft evacuation data [12] and high-rise building evacuation data (starting with interviews of World Trade Center occupants) [13].

Finally, there are three potential opportunities for collecting emergency evacuation data: before, during, and after an incident. Before an incident, a research team could pre-install equipment to capture building evacuation. Motion sensors, connection to the fire alarm system, or remote manual activation could potentially initiate data collection. During an incident, the one agency certain to respond is the fire service. Therefore, deployment of data instrumentation on the fire apparatus or as part of the firefighter turnout gear would ensure deployment to the scene, though the incipient stages (if not the entire duration) may be completed prior to the arrival of the fire service and large segments of the evacuation process may be missed. Finally, the most common opportunity to collect emergency evacuation data is after the incident is complete. Among other problems, documenting an event afterwards suffers from well-documented difficulties of human memory recall, loss of building components during the incident, lack of situation awareness by key personnel, and incomplete cooperation. While the challenges are significant, it is critical to develop infrastructure to support capture of data from emergency building evacuations.

Grand Challenge #3: Embrace variance

While the vast majority of current generation egress models are deterministic, pedestrian movement and building evacuations are highly stochastic processes. Evacuate the same building with the same people starting in the same places on consecutive days and the answers could vary significantly.

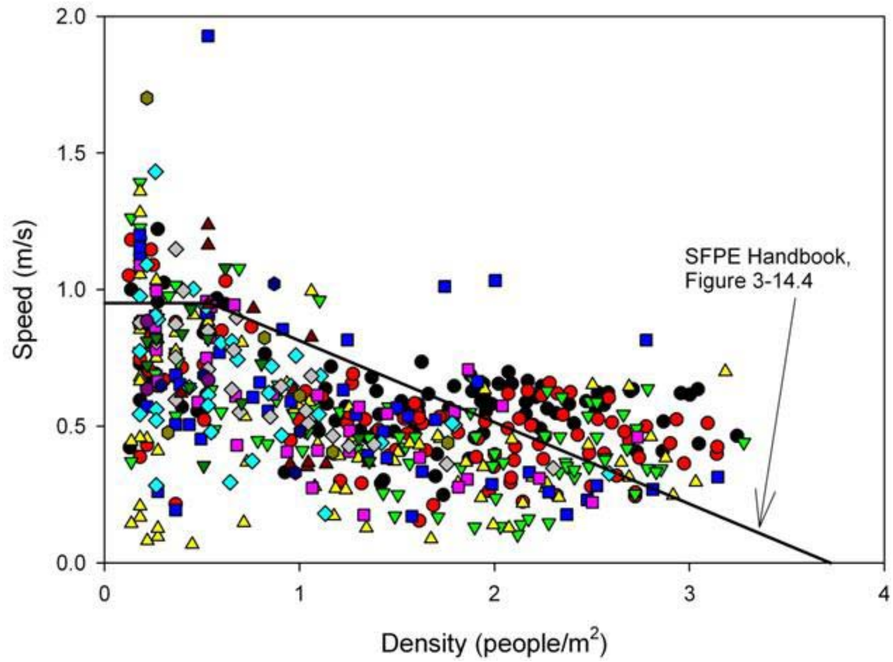

Fig. 1. Relationship between speed and density in stairwells [from Peacock, et al].

The PED community must move away from terms such as "average" for modeling inputs and "evacuation time" for modeling output. Tools and techniques which manage distributions of inputs and outputs should be developed and broadly implemented. Figure 1 shows the substantial variance inherent in stairwell evacuation speeds in four high-rise buildings [14]. The importance of variance is reflected in the dependence of one occupant's evacuation speed on the surrounding occupants. A slow-moving occupant will likely reduce the movement speed of surrounding occupants. Many simulation models currently employ singular values for movement speed (horizontal, descending, etc…). Model inputs which should be accounted for using distributions include number, location, and capabilities of occupants.

Lord, et al. discuss the role of distributions in modeling inputs and model results [15]. As shown in Figure 2, probabilities should be attached to the building evacuation time distributions and a discussion of acceptable risk should take place in every nation and community. For example, using the results of Figure 2, a building authority could specify a confidence level (99 percent) that a building would be evacuated by a certain time (in this case, roughly 400 seconds). Presumably, the evacuation time requirement is related to the onset of untenable conditions (which would, itself, have a distribution and interact with the evacuation terms), including a safety factor.

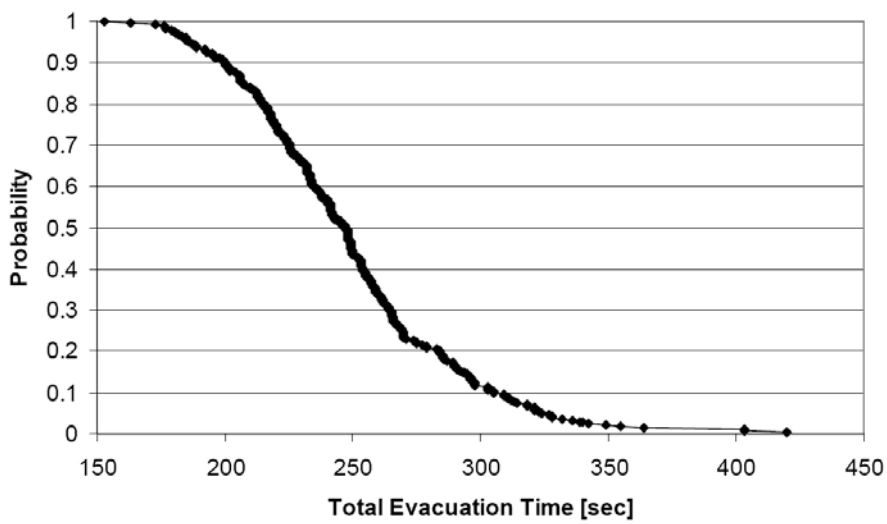

Fig. 2. Probability that an evacuation of the building will be complete [from Lord, et al].

Explicitly acknowledging that the design includes a finite probability that occupants will not successfully evacuate the building will encourage a more informed discussion about local level of acceptable risk.

In order for the PED community to fully embrace variance, there are several key steps: education, tools, and communication. First, the mathematics and logic of distributions must be taught to the stakeholders, starting with students and including engineers, architects, regulators, and building owners and managers. A fluency in distributions and acceptable risk amongst all parties will inform decision-making in a more powerful and consistent manner. Second, tools for capturing, manipulating, and displaying distributions must be incorporated into simulation tools. When capturing and presenting building evacuation data, distributions (rather than means) should be utilized, when possible. Rather than singular movement values and a singular resulting building evacuation time, simulation models should require distribution parameters or links to public datasets (utilizing distributions). Monte Carlo techniques, fractional factorial, or other calculation methods could be used to produce probabilities of outcomes.

Grand Challenge #4: Integrate results of evacuation models with fire models to enable accurate and reliable performance-based design

For the fire safety community, integration of egress modeling calculation with fire modeling calculations resides at the heart of performance based design. However, success requires several advances from the current state-of-the-art, including quantification of the ability of both the egress models and the modelers to produce reliable and repeatable results, development of standard egress modeling scenarios, and accounting for the interactions between the fire and the occupants.

The calculation of Available Safe Egress Time (ASET) through computational fire modeling is substantially more advanced than current-generation predictions of Required Safe Egress Time (RSET) using occupant egress models. While the increased investment in the scientific principles of fire science have exceeded the investment in building evacuation science, the fire modeling community has also engaged in activities which could also benefit the egress modeling community. The fire science community has initiated the first efforts to conduct round robin assessments of fire model performance to establish the strengths, weaknesses, and opportunities for both fire modeling methods and user capabilities [16]. Additionally, the fire science community has established a standard guide for evaluation of fire model predictive capability [17]. A round robin exercise and a validation guide would be informative to the egress modeling community in order to establish state-of-the-art and inform future scientific investments.

Evacuation scenarios, equivalent to the performance-based design required design fire scenarios [18], should be developed for building evacuation. Lower-probability, higher-consequence scenarios (such as a fully occupied building with 50 percent of the exits out-of-service) should be blended with higher-probability, lower-consequence scenarios ('typical' occupant load with all exits available). An example, based upon analysis of New Zealand fire incidents and casualties, was presented at the 8th Int. Conf. on Performance-based Codes and Fire Safety Design [19]. Methods for combining the outcome distributions from the fire scenarios and the evacuation scenarios in a meaningful way that can be understood by the design and regulatory communities for safe and cost-effective building design must be developed prior to realization of the full potential for performance based design.

Finally, a science-based bridge between the effects of the fire and the occupants must be established. The interaction of the occupants with the constraints imposed by the emergency (e.g., people evacuating through smoke) has implications for a host of disciplinary contributions, including toxicology, psychology, sociology, architecture, and engineering. Establishing the causal and distributional outcomes for interactions will enable more precise understanding of the (sub)lethal effects on individuals and the effects on overall evacuation outcomes.

Grand Challenge #5: Embrace technology

Given the paucity of data on simple concepts (such as stairs), it is unsurprising that virtually no data exist for use of technology to improve people movement or building evacuation effectiveness. However, technology can be applied to improve movement speed (elevators, e.g.), improve situation awareness (integration of building sensor technologies, e.g.), or create new egress pathways (alternative escape devices, e.g.). The Rethinking Egress workshop [20] in 2008 identified over 400 alternatives for improving the state-of-the-art in building evacuation, often through novel application of existing technologies from other disciplines.

For the majority of these technologies, there are virtually no experimental data, incident data, theoretical models, or computational algorithms to encourage adoption of more effective strategies. A principal challenge associated with collecting data about the effectiveness of new technology, however, is a "chicken or egg" argument: technology is unlikely to be adopted until empirical evidence proves the utility and empirical evidence is difficult to gather until the technology is adopted. The PED community must lead the way in enabling the enhancements by proactively seeking and developing technologies through data and models.

A novel model for the widespread adoption of new technology was demonstrated by the American Society of Mechanical Engineers (ASME) A17.1 Task Groups on Use of Elevators by Occupants (and Firefighters) for Evacuation (or Access) During Fire Emergency. As a result of having little or no research data to base recommendations for changes to codes and standards, the open-participation task group used an ISO standard hazard analysis methodology [21] over a five year period to systematically address design and implementation hazards for use of elevators by occupants and firefighters during a fire in a high-rise office building. The rigorous process has involved diverse stakeholder participation, thousands of hours of analysis and discussion, and a hazard analysis stretching over 300 pages. The rigorous hazard analysis method was partially responsible for the ready adoption of this new technology in U.S. model codes (International Building Code [22] and Life Safety Code [23]). Individuals with expertise in PED –related disciplines should be significant leaders in efforts such as the ASME A17.1 task groups and future efforts to enable the adoption of PED technologies.

Conclusions

The emerging discipline of PED has many challenges and limited resources. For the field to mature, the community must identify and adopt theoretical and computational approaches which have sound basis in experimental and emergency incident science. Designers and regulators must have standards of practice and computational tools which embrace the full distribution of scenarios and solutions. The preceding grand challenges are merely a starting point for a greater community-inclusive discussion. An interim goal is to develop a focused, consensus agenda on research priorities which will maximize the impact of limited research investments. Ultimately, when the outcomes of these identified goals are widely available and understood, occupants will be able to use and evacuate structures more reliably, efficiently, and with less total cost to society.

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