ELSEVIER

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety





Effect of trained evacuation leaders on victims' safety during an active shooter incident

Cristian Arteaga ^a, JeeWoong Park ^{a,*}, Brendan Tran Morris ^b, Sharad Sharma ^c

- a Department of Civil and Environmental Engineering, University of Nevada Las Vegas, Las Vegas, NV 89154, United States
- ^b Department of Electrical and Computer Engineering, University of Nevada Las Vegas, Las Vegas, NV 89154, United States
- ^c Department of Information Science, University of North Texas, Denton, TX 76203, United States

ARTICLE INFO

Keywords: Active shooting Evacuation leaders Agent-based simulation Social forces model

ABSTRACT

Trained evacuation leaders in emergency offer the potential for improved decision making and evacuation. Compared to victims, trained evacuation leaders can make educated assessments of the situation based on their training, knowledge of the facilities, and additional details about the incident, which enables them to guide victims in choosing a safe departure time and evacuation route. Despite a general understanding about the benefits of such leaders in evacuation, mass shooting cases require a separate attention because these cases are more complex with different behavioral decisions, not just running away, with a continuously changing source of the hazard source, the shooter. This study develops a simulation model package and evaluates the effect of trained evaluation leaders on the victim safety during an active shooter incident. The study leverages sophisticated human motion dynamics models and human behaviors supported by past literature in an agent-based model. The study varies several parameters (e.g., occupancy, firing rates and gun range, and victims' decision of running or hiding) in this simulation to draw generalized conclusions on the leaders' impact on various scenarios. The results reveal general findings with several interesting points. Overall, increased leaders' presence contributes to fewer fatalities. Even few trained leaders, compared with none, can considerably improve victim safety. Even if leaders are not uniformly positioned, they still provide substantial benefits for victim's safety. The leaders' benefits were consistently found in various parametric studies (e.g., number of leaders, occupancy, leaders' strategic placement, gun range, and shooting rate) that support the mentioned findings.

1. Introduction

Active shooters constitute a major public health issue, as the increasing frequency and severity of these events have catastrophic outcomes for communities. Statistics collected by the Federal Bureau of Investigation (FBI) reported 191 active shooter events between 2010 and 2018 in the United States, resulting in a total of 1,851 fatalities (FBI, 2019). These statistics show a clear increasing trend in frequency and number of fatalities as a result.

Victims' decisions are one of the key safety mechanisms to safeguarding their lives during an active shooter incident. Training and preparedness programs for these types of incidents focus on teaching the "Run, Hide, Fight" tactics (FBI, 2022), which advise running when there is an active threat, hiding if escaping is not possible, and fighting as a last resort if facing imminent danger. If properly implemented, these tactics can make a significant difference in victims' safety; however, unknowingly, victims might put themselves at a higher risk by either running or hiding when it is unsafe to do so. This is especially true because victims are not necessarily equipped with information (e.g., geographical knowledge and escape route) to make an informed decision, especially with a highly alerting status in an emergent situation. Making these decisions individually or as a group can be difficult in an emergency scenario, as the urgency and stress of the situation may hinder clear and swift decision-making. Therefore, training evacuation leaders to react to an active shooter incident is a countermeasure with significant potential to enhance victims' safety.

In the event of an active shooter incident, some civilians or personnel of an establishment may need to play the role of evacuation leaders. Examples of these potential evacuation leaders include but are not limited to security guards at malls and crowded events, teachers at schools and universities, and staff members at hospitals and public buildings. Experience from past emergency situations suggests that

E-mail address: jee.park@unlv.edu (J. Park).

^{*} Corresponding author.

evacuation leaders can help save lives. For instance, during the Aztec school shooting in 2017, a substitute teacher rescued her 16 students by quickly reacting and hiding them in a safe location (CBS News, 2017). By the time the shooter entered the classroom and fired multiple rounds, all of the students were already in a safe location thanks to the quick actions of the teacher. Another example, despite being a different type of attack than shooting, from the 9/11 World Trade Center Attack in 2001, highlights the importance of evacuation leaders that a security guard guided the evacuation of more than 2,700 employees and saved their lives (Sisk, 2019). Finally, in the Westgate active shooting in 2020, an off-duty Airforce member is credited with helping save 28 people by guiding them to a restaurant kitchen, hiding them, and securing all the access doors (Diaz-Gorsi, 2021).

Thus, providing training to some personnel in establishments is a strategy with great potential to help save lives in the event of an active shooter. This is especially valuable for cases (e.g., public leisure/convention places) where training all building occupants for these types of incidents is unfeasible for several reasons. For instance, past studies suggest that involving young students in active shooter training increases their feelings of fear and the impression that there is more likelihood of these events occurring (Peterson et al., 2015). Public malls, convention centers, and public leisure places such as casinos have different public users each day, making the training of all possible users impossible. This could be addressed to some extent by training only a subset of volunteer leaders for these incidents. Therefore, this study seeks to investigate the impact of trained evacuation leaders on the consequence of an active shooting event with respect to fatalities.

2. Literature review

This section discusses past studies in the field of computer simulation for active shooter incidents and preceding scientific efforts in modeling of evacuation leaders for emergency situations. The discussion in this section seeks to 1) highlight the plausibility of using computer simulations to study active shooter incidents by describing the advantages of agent-based modeling (ABM) over unfeasible real-life drills and reviewing previous scientific efforts in this field, and 2) review the current state of knowledge in modeling leaders in emergency situations and identify feasible approaches to simulate evacuation leaders and research gaps from past literature.

2.1. Computer simulation of active shooter incidents

Past research in mass shooting incidents primarily focuses on the sociological and statistical aspects of previous incidents, such as the motivations of the shooters; their relationships with the victims; the number of incidents in different years and regions (historical and demographical features of incidents); the number of casualties; and the genders, ages, and ethnicities of the shooters (Agnich, 2015; Haghani et al., 2022; Metzl & MacLeish, 2015; Muschert, 2007; Towers et al., 2015; Zhu et al., 2020). Although these types of data and information elucidate the significance of this topic, they are not able to provide a pragmatic approach to mitigate the detrimental consequences of these incidents. Perhaps one limitation for research on pragmatic approaches may pertain to the impracticality of implementing experiments that involve the real responses of people. This limitation is twofold: 1) potential injuries may happen, and participants may experience trauma if such experiments occur without notice (Briggs & Kennedy, 2016); and 2) difficulty to emulate accurate evacuation situations if early notice is given. Due to these limitations, computer simulations of active shooters become a practical approach to evaluate potential countermeasures to reduce fatal outcomes during these incidents.

ABM is one of the most reliable simulation models because of its ability to realize heterogeneous behaviors to simulate complex interactions between autonomous agents (Bonabeau, 2002; Khodabandelu et al., 2020; Khodabandelu & Park, 2021). As a result, several recent

studies have adopted ABM models for active shooter simulations to evaluate the effect on the reduction of fatalities due to factors such as fighting the shooter (Briggs & Kennedy, 2016; Park & Arteaga, 2019); victims' behaviors (Abreu et al., 2019), controlling access and having concealed carry individuals (Anklam et al., 2015); deployment and coverage of in-place systems to detect shooters (Cho et al., 2019; Lovejoy et al., 2021); and spatial characteristics of the evacuation environment (Arteaga & Park, 2020). These studies provide valuable insights for the analysis of active shooter incidents, and they have highlighted the value of ABM for simulation of these incident types, for which conducting reallife drills is unfeasible. However, past research is limited to the analysis of active shooter incidents under several oversimplified assumptions of pedestrian dynamics and collective behavior. For instance, to the best knowledge of the authors, only one of the previous studies (Arteaga & Park, 2020) used a model of pedestrian dynamics to realistically simulate critical evacuation phenomena such as bottlenecks at exits. None of the previous simulation-based studies consider that the behavior of victims can be highly influenced by the actions of other victims nearby. This can be a strong limitation, as collective behavior is a key consideration for an accurate representation of pedestrians in computer simulations (Templeton et al., 2018). This research thus seeks to address the limitations of past studies by integrating a realistic model of pedestrian dynamics by modeling collective behavior in the presence of trained evacuation leaders.

2.2. Modeling of leaders in emergency evacuations

Past scientific efforts on the simulation of leadership behavior for emergency evacuations can be divided into two subgroups. Studies that model the leadership behavior from a physics or motional standpoint, and studies that model leadership behavior from an information-sharing perspective. The first group of studies extends well-known models of pedestrian motion, such as the social forces models of pedestrian dynamics (SFM) (Helbing & Molnár, 1995) to incorporate the leader--follower behavior (Hou et al., 2014; Ma et al., 2016; Xie et al., 2022; Yang et al., 2016). These studies take advantage of the vector notation of the SFM to alter the movement direction vector or driving force of pedestrians and re-orient them towards an evacuation leader in their vicinity. This strategy enables the incorporation of the leader-follower behavior while maintaining a realistic model of pedestrian dynamics. However, a potential limitation of the strategies adopted by these studies is the apparent inability to extend these models for usage in large building configurations. All of these studies use a single-room configuration in their experiments and analyses, as the strategy of redirecting the direction vector of pedestrians towards leaders stops working once the leaders exit the room.

The second group of studies assumes that leaders share information with other pedestrians during evacuation in order to help them evacuate more efficiently (Han & Liu, 2017; Pelechano & Badler, 2006; Qingge & Can, 2007). Examples of shared information include but are not limited to blocked exits, potential evacuation paths, and alternative exits. A potential advantage of these studies is that the information sharing strategy works well even for large building configurations. Regardless of the strategy used to model the leadership behavior, former studies have concluded that the presence of trained leaders has a positive effect on evacuation efficiency.

Although past research has shown the value of trained evacuation leaders for emergency situations, findings from these studies may not apply entirely to active shooter incidents, as these types of incidents have unique characteristics that require special considerations for the role leaders take during evacuation. First, the existence of "hiding" as a potentially safe alternative in active shooter incidents differs from other emergencies, such as fires or earthquakes, where evacuating maximizes the victims' safety. Second, in active shooter incidents, the threat is an autonomous agent that moves around while seeking to maximize damage and acts reactive to the movement of victims, as opposed to other

types of emergencies, such as natural disasters, in which the threat is independent of the actions of victims. Considering these factors, the risk condition depends on available routes and the varying levels of danger while evacuating, which all adds uncertainty in decision making. If trained evacuation leaders are present on an active shooting site, they are in the best position to make the most educated decisions regarding courses of action, as they account for potentially available resources such as geographical knowledge, escape routes, and may be able to identify the shooter's location. To the best of our knowledge, no previous study exists to evaluate the effect of trained evacuation leaders on victim safety during an active shooter incident.

3. Research objective and scope

The primary objective of this study is to investigate the effect of trained evacuation leaders on saving lives during an active shooter event. Specific parameters of interest are the number (that is, density or proportion) and positioning of trained evacuation leaders on the numbers of fatalities. In addition, this study evaluates scenarios with varying firing rates and range of the gun used by the shooter as well as the victims' decision of running or hiding to draw generalized conclusions on the leaders' impact on various scenarios. This study uses an ABM tool to develop statistically meaningful data from a large number of computer-based simulations. Particularly, the study adopts an agent-based behavior modeling technique (Bonabeau, 2002) that successfully offers an alternative means, instead of conducting unrealistic real-time drills, to simulate behaviors identified by past research (Arteaga & Park, 2020; Cho et al., 2019), thus demonstrating its effectiveness in active shooter events.

The scope of this study includes the development of the simulation model, the design of the experimental setup to conduct the proposed evaluation, and the analysis of the results. The development of the simulation model involves the design of the behavioral rules that the agents (i.e., victims, leaders, and shooters) follow during the simulation, as well as the development of the social forces model of pedestrian dynamics. This study focuses on the simulation of incidents that include a single active shooter, as past studies suggest that 95 % to 98 % of active shooter incidents involve a single perpetrator (Lankford, 2019).

4. Methodology

This section describes the developed ABM model and the experimental setup adopted to conduct the proposed evaluation. First, we describe the ABM model by detailing the actions of each agent (i.e., victim, leader, and shooter) that the agent follows during the simulation, the model of pedestrian dynamics used to model the victims' movements, and additional behavioral rules incorporated into the model. After explaining the details of the agents in the simulation model, we present the experimental setup with various scenarios and changes in parameters to obtain a statistically meaningful number of datasets for subsequent scrutiny.

4.1. ABM model

This section details the behaviors of the victims, leaders, and shooter incorporated into the ABM model. The crowd modeling literature proposes several theories, such as the Panic, Emergent Norm, Social Attachment, Self-Categorization, and Protective Action Decisions theories, to explain the behavior of crowds in emergency situations (Shipman & Majumdar, 2018). The developed ABM model incorporates some of the behavioral aspects specified in these theories, especially those related to collective behavior. For instance, leaders providing instructions to victims in their room and in other rooms visited during the evacuation can be associated with aspects of the Emergent Norm (Lemonik & Mikaila, 2013) and Social Attachment (Mawson, 2005) theories. In addition, the fact that evacuation leaders need to shift their

self-perception as individuals and think of themselves as group guides can be associated with aspects of the Self-Categorization theory (Turner et al., 1994). Thus, the developed ABM models victims beyond a panic perspective, in which people are assumed to have mob mentally and behave irrationally, but instead it adopts a social and affiliate perspective, which aligns better with current scientific understanding of behavior in emergency situations (Aguirre et al., 2011).

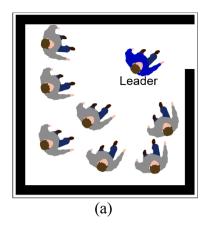
4.1.1. Victims' behavior

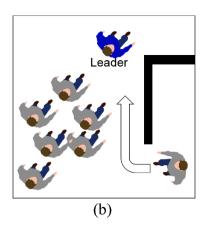
This study models victims' behavior based on the run, hide, and fight tactics, which provide a reasonable framework for simulation of victims' actions, as described by previous studies (Anklam et al., 2015; Cho et al., 2019). As the simulation runs over time, victims may make multiple decisions among their feasible options per their situation over time progression. The simulation starts with a shooting event; therefore, this study sets certain behaviors as default while allowing behavioral changes over time. Victims start running as soon as they hear gunshots. Although in reality may exist an information gathering period, especially for people who may be distant, in which victims take some time to become aware or react to the situation, the simulation assumed this time period as zero to standardize the outcome of multiple simulations. In addition, this study incorporates the hiding option by setting it at 20 % for initial analysis with additional follow-up analyses with the hiding proportion parameter. This proportion of hiding victims was set based on the analysis of materials from past active shooter incidents, such as interviews, documentaries, and victim's testimonies (Benitez et al., 2016; Browne et al., 2017; Burke, 2022). In these materials, it was noticeable that most victims of these incidents tend to run, but at the same time, an appreciable proportion of victims prefer to shelter in place. Besides the 20 % default proportion of hiding victims, this study tested other proportions (10 % to 40 %) of hiding victims to evaluate their effect on the simulation outcome, as described in the Results and Discussion section.

The simulation model does not include a fighting behavior for victims for two main reasons. First, the fighting behavior may cause the simulation to conclude early when the shooter is subdued, which hinders the observation of the effect of trained evacuation leaders on victims' safety. As such, this defeats the purpose of this research's objective. Second, run and hide are the primary actions recommended by the FBI in the event of an active shooter, as fighting should be used only as a last resource when facing imminent danger (FBI, 2022). Likewise, we exclude the freezing behavior for two reasons. The number is so small being insignificant for analysis, and freezing parties will not necessarily follow the leaders' guidance, which would only add complexity to the analysis without any benefit in the course of study toward accomplishing the objective.

The above descriptions pertain to two victim behaviors in two cases, as the default mode in the simulation. The simulation also takes into account victims' behavior in the presence of trained evacuation leaders. With simulation progression, victims, while following their default behaviors, continue to seek an evacuation leader. Fig. 1 illustrates three behaviors that victims may take upon availability of a leader. As discussed previously, trained leaders have a superior ability to make the most educated decision of course of action (see the leaders' behavior section) as they are assumed to be trained to leverage resources such as geographical knowledge, escape routes, and possibly the shooter's location. Victims follow the leader, as shown in Fig. 1(a), given the condition that the leader makes the best educated actionable decision. Victims find a leader and follow the leader by switching the original route, if needed, as shown in Fig. 1(b). Finally, when the evacuation leader switches to a safer evacuation route, victims continue following them through this new route, as illustrated in Fig. 1(c). If a leader is not present, victims follow the original run and hide tactics. Victims who do not have an evacuation leader may find one while running throughout the building and change their behavior accordingly.

These leader and victim behaviors incorporate the collaborative and





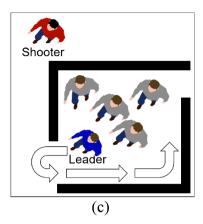


Fig. 1. Modeling of victims' behavior in presence of trained evacuation leaders: (a) victims following the nearest leader, (b) victims identifying a leader while evacuating, and (c) leader and victims switching to a safer route.

herding behavior usually manifested during emergency situations (Dezecache et al., 2017; Templeton et al., 2018). This research thus uses ABMs developed in past studies as reference (Arteaga & Park, 2020; Cho et al., 2019), and expands the behavioral rules of victims to take the presence of evacuation leaders into account and conduct the proposed investigation.

To add the realism of human evacuation dynamics, it is important to account for the effect of crowd dynamics, especially when modeling a computer simulation for emergent evacuation. When running along a straight path (e.g., corridor), people can maintain consistent speeds given that the speed variation among people is not highly considerable, so the modeling of evacuation dynamics may not be critical. However, in indoor evaluation scenarios, speed variations are expected due to many possible bottleneck effects at geographical changes on the map (e.g., turning, passing through doors and entrances, and merging of spaces). In this regard, this study models the motion of victims using the Social Forces Model (SFM) of pedestrian dynamics (Helbing & Molnár, 1995), which account for various parameters (e.g., density, direction, and interactions with nearby people) to accurately describe human escape dynamics. The use of SFM enables realistic modeling of key evacuation phenomena such as clogging doors and exits and the faster-is-slower effect (Parisi & Dorso, 2007; Suzuno et al., 2013). Similar to Arteaga and Park (2020), this study adopted the SFM parameters specified in Moussaïd et al. (2009), which are based on experiments in a laboratory environment with real humans. This study modified the pedestrian desired speed to better reflect that people tend to walk faster in emergency scenarios. In addition, people have variations in speeds, which further impacts the pedestrian dynamics in a crowd. To further account for this speed difference, we set the desired speeds based on a normal distribution with a mean 1.9 m/s and standard deviation 0.4 m/s, where 1.9 m/s corresponds to the speed at which an average adult human switches from walking to running (Kram et al., 1997).

As detailed in the literature review section, a group of past studies have proposed modified versions of the SFM to incorporate leadership behavior in pedestrians (Hou et al., 2014; Ma et al., 2016; Xie et al., 2022; Yang et al., 2016); however, these studies are limited by the nature of their SFM development, which has been tested only in single-room configurations and cannot be easily adopted to our simulation scenarios. Therefore, this study uses an alternative strategy corresponding to the second group of the leadership behavior modeling, which consists of leaders sharing information with victims. Shared information can include the safest route to evacuate the building as well as the best course of action (i.e., running or hiding) to safeguard one's life.

4.1.2. Leaders' behavior

In the ABM model, leaders help nearby victims on 1) determining whether running or hiding is the safest course of action, and 2) finding an evacuation route to safely exit the building. We based these two aspects on a review of past work in active shooter training, in which we identified that key roles for leaders during evacuation are helping victims on decision making and finding evacuation routes (Jonson et al., 2020; Tucker & Hemphill, 2020; Zhu et al., 2022). The simulation model assumes that the leaders have received a training that enables them to 1) be highly familiar with the building layout and know all the evacuation routes and 2) identify whether it is safer to hide or run based on the position of the shooter. The ability of the evacuation leaders to know the exact position of the shooter may seem like a strong assumption; however, it is feasible that a leader can estimate the shooter's position based on the training and knowledge they have gained, communication with other leaders, and the potential availability of in-place shooter detection systems (SDS, 2018), which are commercially available and have proven to be a reliable technology to detect the location of a shooter. In addition, there has been considerable on-going research (Akman et al., 2018; Cho et al., 2019; Li et al., 2019; Lovejoy et al., 2021; Lu et al., 2021) and industrial (SDS, 2018) activities to identify shooters or unique individuals, making this assumption reasonable in our designed simulation model. By knowing the position of the shooter, leaders can leverage their knowledge/experience/familiarity about the site to assess whether running or hiding is the safest alternative. Leaders run and direct victims to do so when there exists a safe evacuation route, otherwise, they hide until finding an ideal time to run.

To set an analytical or objective procedure for action decision making, we used a route risk assessment model adopted from a past study (Masoumi et al., 2019). The leaders are modeled to use this risk model to check the risk of all routes, if multiple, and decide the best course of action. The risk of an evacuation route r ($Risk_r$) is formulated as a function of the distance ($Dist_r$) between the route and the shooter, as shown in Equation (1), to reflect the reduced risk level over the distance.

$$Risk_r = \begin{cases} \sqrt{(FR - Dist_r)/FR} & if \ Dist_r < FR \\ 0 & otherwise \end{cases}$$
 (1)

where FR is the firearm range of the gun used by the shooter. This risk assessment model is based on the given distance of a given point; however, an evacuation route is composed of multiple points, p, in its route. Accordingly, we check all points and find the minimum of all the distances, $Dist_p$, between the shooter and the points in the route that are visible to the shooter as shown in Equation (2). This minimum distance, when used in the risk equation, produces the largest risk in that route, which is the critical value the leaders need to consider.

$$Dist_r = \min(\{Dist_p \text{ for all points } p \text{ visible to the shooter}\})$$
 (2)

At the beginning of the simulation, leaders make an assessment of whether running or hiding is the best course of action when the shooter

starts shooting. If there exists a safe evacuation route, which corresponds to a route with zero risk level, the leaders run and direct victims to follow such a route; otherwise, leaders hide and direct their victims to do so when there is no safe evacuation route. Over the course of time, leaders continue to use the route risk function to look for a safer route for evacuation. If a better route is found, leaders switch to the route with the lowest risk level. This is continuously evaluated, and the result is reflected as the shooter moves around during the simulation until the simulation ends. Such a model is important because the effectiveness of leaders' presence is evaluated across computer simulations, which should operate based on the same principles for consistency and reliable evaluation.

4.1.3. Shooter behavior

Shooters inflict harm on victims depending on several factors, such as the characteristics of the gun (e.g., gun type, firing rate, firearm range, magazine capacity, and ammunition type) and his/her specific skills (e.g., shooting accuracy). An attempt to incorporate all these factors in a simulation study is unfeasible and unreliable. It would require comprehensive ballistic models for different types of guns and shooter skills, which, as a result, would produce varying and thus not meaningful results. In addition, such a simulation would only add unnecessary complexity to the investigation of this research, focusing on the leader's impact on the safety of victims. Therefore, the study uses only two parameters (i.e., the firing rate and firearm range), as they reasonably reflect the characteristics of the gun-related parameters (e.g., gun type, magazine capacity, and ammunition type). For the firing rate and firearm range, this study includes an analysis that demonstrates that the use of different values for these factors may alter the fatality result on a single simulation, but it does not affect the overall trends that this study seeks to understand by evaluating scenarios based on consistent settings. The parameter values tested in this analysis are detailed in the Experimental Setup section.

In addition to hardware-related characteristics of the shooter, the study models the shooter as an autonomous agent in the ABM model. At the onset, the shooter starts to kill the closest victim in his/her field of view while visiting all the closest spaces/rooms in the building sequentially. Beyond killing victims who are in the line of sight, the study incorporates killing hidden people supported by past incidents, noting that shooters do not simply kill victims within their sight, but they also scan the building looking for hiding victims (Blair & Schweit, 2014; FOX News, 2018; Zhu et al., 2022). Specifically, this study models a proportion of victims as hiding instead of modeling all victims as running, and the simulation accounts for corresponding differences. Hiding victims have reduced chances of getting killed while they are still vulnerable to being found and shot. Therefore, we introduced an additional parameter in the simulation to model the probability of the shooter killing a hiding victim, which can also be understood as the probability of the shooter finding a victim after scanning his/her surroundings. Similar to the firing rate and firearm range, different values were tested for this parameter, as described in the Experimental Setup section. The simulation ends when the shooter has killed all the people in the building or after 5 min, which, based on a previous study (Anklam et al., 2015), is the average time it takes for law enforcement to arrive in these types of incidents.

4.1.4. Building layout

This study used the building layout shown in Fig. 2, which has been previously used by Cho et al. (2019), and it is based on a portion of a school setting model. This is a 40 m-by-40 m building layout with two

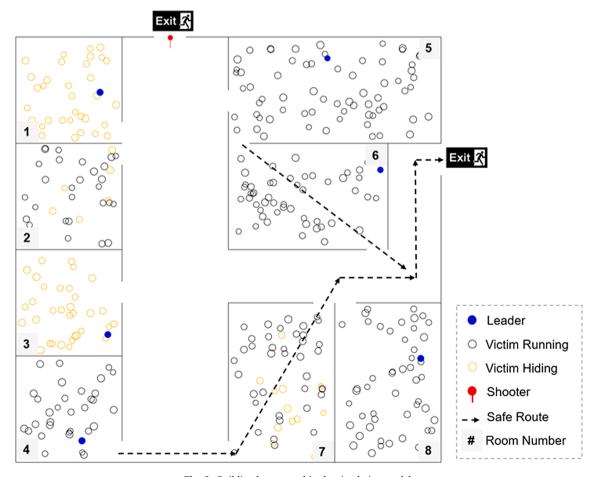


Fig. 2. Building layout used in the simulation model.

entrances/exits located on the north and east sides. This layout incorporates a convenient level of complexity to conduct the proposed evaluation, as it additionally contains several rooms and interconnections, which provides multiple and complex evacuation routes for the victims.

Fig. 2 shows a snapshot of the building layout at the first simulation step, in which victims and leaders are randomly positioned in the available rooms. This figure also provides illustrative examples about several scenarios that distinguish the presence and absence of leaders. For instance, the evacuation routes for the upper rooms (Rooms 1 and 5) experience high-risk levels due to their closeness to the shooter while Room 1 does not have safe evacuation routes and Room 5 does. The leader in Room 1 therefore determines that hiding is the best course of action, as there is no safe evacuation route. Although this option still may not be safe, as the shooter can enter the room and kill victims, it is the best option at the time of decision making. On the other hand, the leader in Rooms 5 evaluates two available routes and identifies that one of them is a safe route while the other is unsafe. Then, the leader runs along the safe route and directs victims to follow. This is illustrated in Fig. 2 with the arrow crossing Room 6 starting from Room 5. These examples provide comparable scenarios that highlight the presence of leaders who leverage their trained resources (e.g., knowledge of the building layout, alternative evacuation route, and shooter's position) to better help victims in evacuation.

Fig. 2 also illustrates an additional scenario in which victims in Room 4 significantly benefit from the guidance of a leader. In Room 4, the leader identifies that there is a safe evacuation route by crossing through Room 7, as denoted by the dashed arrows. The leader from Room 4 also helps victims from Room 7 to a large extent. As the leader and people from Room 4 escape through Room 7, people from Room 7 join this leader's group and follow the same evacuation route. This scenario further highlights the benefits that leaders provide for safe evacuation. On the other hand, without a leader, the victims in Room 2 and 7 may not take the best course of action due to inability to leverage the same resources available to trained leaders.

4.2. Experimental setup

To evaluate the effect of trained evacuation leaders on the safety of victims during an active shooter incident, this study analyses 2,820 simulation executions (94 scenarios repeated 30 times each for statistical significance) with respect to seven parameters, including the number of leaders, leaders' positioning, occupancy density, firing rate, firearm range, proportion of hiding victims, and probability of killing hiding victims. The study first conducts a primary investigation on the first three parameters to analyze the effect of leaders' presence in various environments. The different simulation scenarios in this primary investigation are described below:

- (i) Number of leaders: The number of leaders varied from zero to eight in increments of two. The maximum number of eight leaders corresponds to the number of rooms in the building layout used in this study.
- (ii) Positioning strategy for the leaders: Two positioning strategies were evaluated: uniform and non-uniform. Uniform positioning means that the simulation places the available leaders evenly in different rooms to maximize the coverage of victims with a leader. Non-uniform positioning means that leaders are randomly placed within the available rooms without seeking an even distribution of leaders, which may result in two or more leaders placed in the same room. In such a scenario, one major observable difference compared with the uniform scenario is a possible change of decision. It is possible that a safe route is identified and one of the leaders starts to escape with followers; however, if the situation changes (e.g., the shooter is approaching), the second

- leader can change the decision and guide those who are still in the room differently.
- (iii) Density of people in the building: The tested densities of people include 0.14, 0.34, and 0.54 people/m². These densities correspond to 14, 34, and 54 people in a 10 m-by-10 m room. The 0.54 people/m² value corresponds to the minimum space per student designated in the classroom design standards from the New York State (NY.GOV, 2010).

The primary investigation explored environmental parameters about the leader. The secondary investigation aims to enhance the findings from the first investigation by conducting a sensitivity analysis on the last four parameters of the aforementioned seven parameters. This set of parameters pertains to the shooter and victims, which can be different in various shooting scenarios. Therefore, the second study investigates the shooter-and-victim-related parameters to account for its variability with respect to the impact of leaders in evacuation. Each parameter was evaluated for four different numbers of leaders, which varied from zero to eight in increments of two. The parameters tested in the secondary investigation are as follows:

- (i) Firing rate: the tested firing rates varied from one to four rounds per second. These values are based on conventional firing rates for standard and modified versions of the AR-15 rifle (Andersen, 2022), which is a gun that has been repeatedly used in past active shooter incidents (Smith, 2016).
- (ii) Firearm range: this analysis tested four firearm ranges, varying from 30 m to 60 m at increments on 10 m. These values are based on a previous study by Briggs and Kennedy (2016).
- (iii) Proportion of hiding victims: given that specific guidance does not exist from past studies for the proportion of hiding victims, we tested 10 %, 20 %, 30 %, and 40 % as potential proportions of hiding victims based on the analysis of materials from past active shooter incidents such as interviews, documentaries, and victim's testimonies (Benitez et al., 2016; Browne et al., 2017; Burke, 2022).
- (iv) Probability of killing hiding victims: this analysis tested 20 %, 30 %, 40 %, and 50 % as potential probabilities for the shooter killing hiding victims, which are assumed based on the analysis of materials from past active shooter incidents, similar to the previous parameter.

Each of the simulation scenarios were repeated 30 times to ensure that the observed effects are a result of the evaluated parameters with statistical significance and not a product of randomness. Thus, the repetitions of the 94 simulation scenarios resulted in a total of 2,820 simulation executions. The 94 simulation scenarios are computed as follows. The primary investigation included five varying numbers of leaders, and three varying densities of people that resulted in a total of 30 different simulation scenarios. The secondary investigation tested four different values for each of the four parameters, which were evaluated with four different numbers of leaders, resulting in 64 simulated scenarios. The number of scenarios from both investigations add up to 94.

5. Results and discussion

This section presents data obtained from our 2,820 simulations and its results followed by analysis. To observe the leader's impact during the evacuation, all results were compared with respect to the proportion of fatal victims. The use of fatal victim proportion is a fairer comparison because it is a normalized parameter, allowing relative comparison, unlike the number of fatal victims on an absolute scale. The following subsequent sections present the results and discussion for the primary and secondary investigations, separately. The primary investigation directly changes the parameters related to leaders; therefore, obtained

data and results following various statistical analyses allow us to observe the impact of the leader during evacuation. The secondary investigation changes the parameters associated with the shooter and victim. This additional investigation allows us to observe the impact of these parameters on the leader during evacuation.

5.1. Primary investigation

To understand the effect of trained evacuation leaders on the safety of victims during an active shooter incident, the primary investigation evaluated five different numbers of leaders (i.e., zero, two, four, six, and eight) using two different positioning strategies (i.e., uniform and non-uniform). We first conducted this evaluation at a baseline building occupancy of $0.14~\text{people/m}^2$. We then increased the building occupancy to $0.34~\text{and}~0.54~\text{people/m}^2$ to observe how the increase in density of people affects the observed benefits of having trained evacuation leaders.

Table 1 shows descriptive statistics of the simulation results for the primary investigation. The descriptive statistics include the mean and standard deviation (SD) of the proportion of fatal victims for different numbers of leaders under uniform and non-uniform positioning strategies at a baseline building occupancy of 0.14 people/m². We computed these descriptive statistics across the 30 simulation repetitions for each of the studied scenarios. The "% Decrease" columns show the percentage decrease in proportion of fatal victims with respect to the zero-leader case. This particular value indicates the percentage decrease of the fatal victim ratio with an increase in the number of leaders in the available space.

In both uniform and non-uniform cases, the mean proportion of fatal victims decreases with a greater number of leaders. While this generality is true, our observation yielded a number of intriguing results. The positive impact (reflected in % decrease in the fatal victim ratio) on the uniform positioning case is more considerable than that of the non-uniform positioning case. This is understood generally with smaller standard deviations and larger percent decreases for the uniform positioning case, compared with the non-uniform positioning case. Despite reduced impact with the non-uniform positioning case, the results clearly present positive evidence of leaders' presence in evacuation even when the leaders' positioning strategy is not well devised but randomly placed in the available space.

Generally, we found a larger variance with the non-uniform case, as shown by the SD columns in Table 1. This can be confirmed in Fig. 3, which illustrates the distribution of the proportion of fatal victims for different numbers of leaders positioned uniformly (a) and non-uniformly (b) in the building. The larger variance for the non-uniform case is the result of the uneven assignment of leaders in rooms, which could generate scenarios with multiple leaders in a room at a cost of missing a leader in another room. Multiple leaders in a room largely add two varying effects: 1) multiple leaders can be beneficial for scenarios where one leader exits a room first but fails to safely complete the evacuation for all followers due to situational changes with the risk with a moving shooter. In such a situation, a second leader may help save more people,

Table 1Proportion of fatal victims for different number and positioning strategies for leaders.

Number of Leaders	Proportion of Fatal Victims					
	Uniform Positioning			Non-uniform Positioning		
	Mean	SD	% Decrease	Mean	SD	% Decrease
0	0.51	0.03	_	0.52	0.04	_
2	0.47	0.05	7.2 %	0.47	0.04	10.0 %
4	0.41	0.05	19.4 %	0.44	0.06	15.5 %
6	0.38	0.04	25.2 %	0.40	0.06	22.0 %
8	0.33	0.01	34.5 %	0.39	0.06	23.8 %

especially when changing a decision is necessary. For example, a second leader who has remained in the room can guide the rest of the victims through alternative routes. On the other hand, placing multiple leaders in the same room can be disadvantageous for scenarios where the extra leaders could assist victims in other rooms. Multiple leaders in a given room may offer additional benefits for the victims, but these benefits are outweighed by the additional risk the victims in other rooms experience. Thus, these advantages and disadvantages of multiple leaders in the same room produce a larger variability in the simulation results due to the imbalance in the coverage of victims. Comparing variances of the two uniform and non-uniform cases at high numbers of leaders (e.g., 4, 6, and 8 leaders), the variances become larger. This implies that such situations accounting for the advantages and disadvantages are more frequently encountered, and the effect is included in the variance term in a statistical analysis over multiple simulation runs.

Fig. 3 also expands the results of Table 1 in terms of the decrease in proportion of fatal victims caused by the presence of trained leaders. The solid lines that connect the medians of the different distributions show a downward trend in the proportion of fatal victims as the number of leaders increases. This downward trend is noticeable for both the uniform and non-uniform positioning of leaders; however, the uniform positioning exhibits a steeper and more consistent decrease than the non-uniform positioning. This result suggests that uniformly distributing trained evacuation leaders throughout the building spaces results in enhanced benefits for victims' safety, but even if this is not possible, the non-uniform positioning of leaders also offer important benefits.

Additional analyses with different densities: The results in Table 1 and Fig. 3 correspond to simulation scenarios using a baseline density of people of 0.14 people/m². The following discussion corresponds to the evaluation of scenarios with densities of people increased to 0.34 and 0.54 people/m² in order to observe the variation in the effect of evacuation leaders on victims' safety as the building occupancy increases.

Fig. 4 shows the effect of the number of leaders on the proportion of fatal victims for different densities of people in the building. Fig. 4 indicates that increasing the building occupancy changes the simulation outcomes on an absolute scale, but it does not significantly change the overall trends in reduction of fatalities in a leaders' presence. This confirms the same positive benefits of the leader's presence onsite we discussed previously. This also concludes that increasing the density of people does not significantly change the overall trends that result from the positioning strategy for leaders. Based on the results, even deploying a small number of leaders can make a difference by reducing the fatality rates by 10 % to 20 % in both uniform and non-uniform cases, which are commonly observed in all density cases. In addition, Fig. 4 presents a seemingly counterintuitive result. The plots show a decrease in the proportion of fatal victims with an increased density. However, this is a reasonable result, as this experiment increased the density of people without increasing the ability of the shooter to harm more of them, which results in a lower proportion of fatalities. It is important to note that most mass shooting cases in U.S. history are caused by one shooter.

In terms of variability of simulation results, Fig. 4 shows that cases with higher densities of people had a slightly higher variability of the simulation outcomes. This can be understood intuitively for two reasons:

1) more people mean more variations in escaping and 2) being shot depends on factors, such as proximity to shooter and proximity to escape route, and these factors can vary, resulting in more varying effects with higher densities. An additional insight provided by Fig. 4 is the consistent low variability of results for the scenarios with eight leaders uniformly positioned in the building. In these scenarios, a leader is available in every room, which reduces the randomness associated with leader assignments to rooms and produces more consistent proportions of fatal victims as simulation outputs. Generally, for uniform leader placement cases, the results tend to be more consistent in terms of variability.

Although the results presented in this section pertain to specific mass shooting scenarios, the findings discussed so far are consistent with the results of past studies in other evacuation studies (Hou et al., 2014; Ma

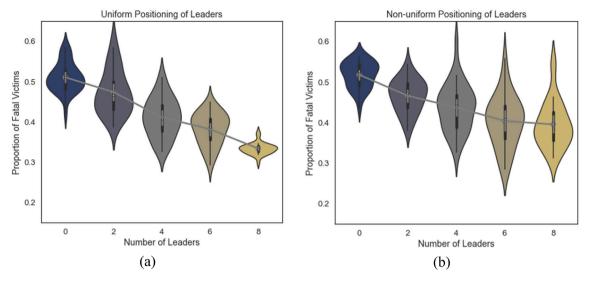


Fig. 3. Effect of the number of leaders on the proportion of fatalities.

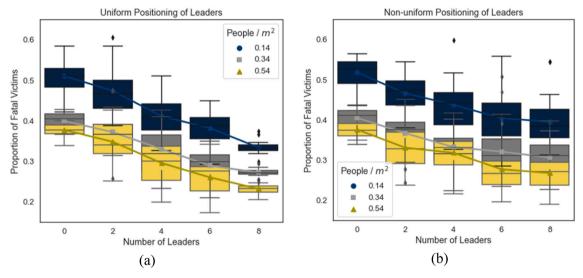


Fig. 4. Effect of the number of leaders on the proportion of fatal victims for different building occupancy levels.

et al., 2016; Pelechano & Badler, 2006). Even a few trained evacuation leaders can produce considerable benefits for evacuation safety. These findings align with the results in Table 1 and Fig. 3, which show that even two evacuation leaders can provide a 7 % to 10 % reduction in the proportion of fatalities. Also, further increasing the number of leaders by a margin of two results in 15 % to 19 % reduction in the proportion of fatalities.

5.2. Secondary investigation

The primary investigation pertained to leaders' presence and its impact on fatalities in a mass shooting event. We conducted this study by statistically analyzing its impact with respect to parameters associated with the leaders' presence. In doing so, the developed ABM model needed to set certain simulation parameters associated with shooters and victims to fixed values because inclusion of too many controlling parameters would not produce meaningful results. As discussed in the experiment setup section, the secondary study investigates the shooter-and-victim-related parameters to account for its variability with respect to the impact of leaders during evacuation. This investigation presents the impact of leaders' presence with respect to four parameters (i.e., the gun firing rate, the firearm range, the proportion of hiding victims, and

the probability of killing hiding victims). The simulations and results are based on a density of people of 0.14 people/ m^2 and uniform positioning of leaders

Fig. 5 presents the simulation results between the proportion of fatalities and the number of trained evacuation leaders across four varying parameters ((a) gun firing rates, (b) firearm ranges, (c) proportion of hiding victims, and (d) probabilities of killing a hiding victim). This figure shows a general decreasing trend in the proportion of fatal victims as the number of leaders increases. This decreasing trend is consistent regardless of the values used for the four evaluated parameters, which confirms the same findings about the effect of leaders' presence observed in the primary investigation even when considered with the parameters of the secondary investigation. Changing the values of these parameters leads to an upward or downward shift in the proportion of fatalities but does not affect the overall decreasing trends. Thus, the parameter values influence the simulation outcome but not the overall trends of interest in this study.

The gun firing rate, shown in Fig. 5(a), is the parameter that produces the most noticeable shifts in the proportion of killed victims, which is an expected result, as this parameter directly influences the number of victims that the shooter can harm. On the other hand, the firearm range, shown in Fig. 5(b), produces a less noticeable shift in the

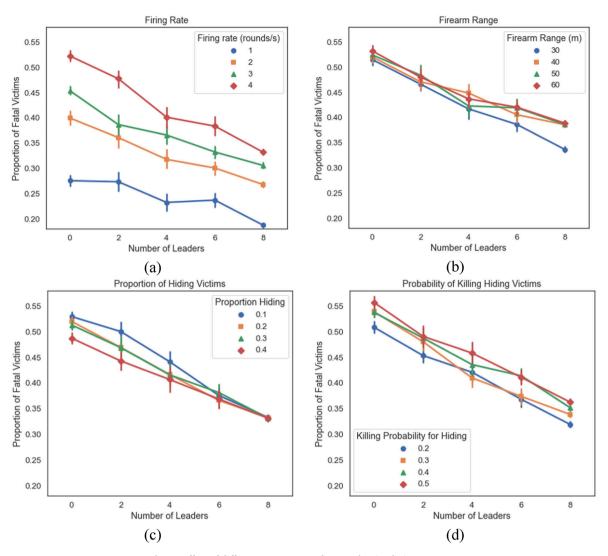


Fig. 5. Effect of different parameters values on the simulation outcome.

proportions of fatal victims, especially for values above the 30 m range. This is a reasonable result given the size of the building layout used in this study, but this parameter could have a more significant effect in larger building layouts. The results of these two parameters suggest that the gun firing rate parameter is more critical than the gun range parameter, especially in a relatively small building.

Although Fig. 5(c) presents a slight decrease in the proportion of fatalities with an increased proportion of hiding victims with low numbers of leaders, the differences are not significant, considering the variations. This decrease is seen only for low numbers of leaders and diminishes as the number of leaders increases, to the point that the effect converges to null for numbers of eight leaders. This is due to the fact that the proportion of hiding victims only affects the behavior of victims when they do not have a trained evacuation leader nearby. Thus, for the eight-leader scenario, all victims follow the course of action indicated by their leader, and no victim is influenced by the proportion of hiding victims' parameter. In reality, persistently hiding victims may exist, but the leaders' assistance should help a hiding victims; therefore, our general results can still be considered valid. This is an interesting result, as the convergence in fatalities for a high number of leaders suggests that the impact of leaders is obvious for victims both in hiding and nonhiding states. Finally, the probability of killing hiding victims, shown in Fig. 5(d), affects the proportion of fatal victims but not to a large extent. This is because there is always a large proportion of victims running (instead of hiding) either by the indication of their leader or by a random

assignment. Thus, the parameter for the probability of killing hiding victims only affects a reduced subset of the victims, which in turn produces a low effect on the proportion of fatal victims as shown in Fig. 5 (d)

In summary, the results of the secondary investigation indicate that the decrease in proportion of fatal victims due to the presence of trained evacuation leaders is consistent regardless of the parameter values used in the simulation. Thus, the trends and insights observed in this study are meaningful and sound despite the parameter values used in the developed ABM model.

6. Conclusions

This study evaluated the number and positioning of trained evacuation leaders on the proportion of fatal victims during an active shooter incident. Due to the infeasibility of conducting real-life drills of active shooter incidents, this study leveraged an ABM technique to conduct the proposed evaluation. The developed simulation model includes an information-sharing strategy to model the leadership behavior and the Social Forces model of pedestrian dynamics to model the motion of victims while evacuating the building. The proposed evaluation was conducted by running 2,820 simulation executions for 94 designed scenarios with a different number of leaders, positioning strategies, and densities of people and further observing their effect on the proportion of fatal victims. In addition, we evaluated different shooter and victim-

related parameters to show that they influence the outcome of the simulations. Although such parameters change the fatality results in an absolute scale, we observed the positive benefits reflected in the overall decreasing trend by trained evacuation leaders. The results of the conducted investigation provide three valuable insights. First, even a few evacuation leaders, compared to none, can considerably reduce the number of fatalities. Second, a uniform positioning of leaders offers the greatest benefits for victims' safety. However, even if leaders are non-uniformly positioned, they still enable a significant reduction in the number of fatalities. Third, the benefits of evacuation leaders for victims' safety are consistent even for high levels of building occupancy.

The insights provided by this study can open the door to further studies and discussions about the importance of evacuation leaders for the safety of victims of active shooting incidents. Evacuation leaders can be especially valuable for cases where training all potential victims of these incidents is unfeasible due to 1) the significant stress and psychological repercussions that exposure to the training of active shooter incidents can impose, especially children, and 2) the impossibility of knowing in advance the visitors of a facility, such as commercial and public buildings. Caution must be exercised when interpreting the insights of this and similar computer simulation studies for active shooter incidents, as these are the results of pure numerical simulations. Providing a validation baseline for these studies is an unfeasible task, as it is unfeasible to compare the obtained insights with outcomes of reallife incidents. However, despite the pure numerical nature of the simulation and results provided by this study, we found that 1) the coherent results that support the benefit of leaders' presence are observed across different simulation parameters even with a lower number of leaders present, 2) the study's results support past studies in leader-assisted evacuation for other types of emergency situations with several unique insights applied to shooting scenarios, and 3) the most reliable benefit is observed when each room is covered by at least one leader due to the reduced variability of unpredictable behaviors by victims.

Although this study aims at incorporating as much realism as possible in the developed simulation model, there are some modeling assumptions that can be further studied in future research to enable better simulation capabilities. First, this study assumed that victims only communicate with their evacuation leader, but in reality, there exists inter-communication between victims, which may affect the outcome of an evacuation. Future efforts can therefore focus on integrating more sophisticated and realistic mechanisms of intercommunication between victims. Second, this study assumed that the evacuation leaders are welltrained individuals able to respond in case of an active shooter incident. In reality, however, there can be spontaneous leaders or first responders that, despite a lack of specific active shooter training, may impact behaviors of others. In these cases, the simulation may need to account for the potential imperfect training of these spontaneous leaders and their effect on the outcome of the incidents. Third, the simulation assumed active shooter events involving a single perpetrator; however, scenarios with multiple perpetrators are feasible in reality despite being rare. Therefore, future work can focus on evaluating the extent at which multiple perpetrators increase the risk of victims during evacuation guided by trained leaders and its impact on decision-making, consequence of the event, and others. Finally, future studies can investigate and incorporate more sophisticated risk-assessment models into the simulation. Specifically, risk models that dictate victim's decision making and choice of evacuation routes based on environmental clues, such as hearing gunshots or victims yelling, can help increase the modeling capabilities of the simulation.

CRediT authorship contribution statement

Cristian Arteaga: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **JeeWoong Park:** Writing – review & editing, Validation, Supervision,

Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Brendan Tran Morris:** Investigation, Resources, Writing – review & editing, Project administration, Funding acquisition. **Sharad Sharma:** Resources, Project administration, Investigation, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This material is based upon work supported by the National Science Foundation [Award #: 2131151]. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

- Abreu, O., Cuesta, A., Balboa, A., Alvear, D., 2019. On the use of stochastic simulations to explore the impact of human parameters on mass public shooting attacks. Saf. Sci. 120, 941–949. https://doi.org/10.1016/j.ssci.2019.08.038.
- Agnich, L.E., 2015. A comparative analysis of attempted and completed school-based mass murder attacks. Am. J. Crim. Justice 40 (1), 1–22. https://doi.org/10.1007/ s12103-014-9239-5.
- Aguirre, B.E., El-Tawil, S., Best, E., Gill, K.B., Fedorov, V., 2011. Contributions of social science to agent-based models of building evacuation. Contemporary Soc. Sci. 6 (3), 415–432. https://doi.org/10.1080/21582041.2011.609380.
- Akman, Ç., Sönmez, T., Özuğur, Ö., Başlı, A.B., Leblebicioğlu, M.K., 2018. Sensor fusion, sensitivity analysis and calibration in shooter localization systems. Sens. Actuat. A 271, 66–75. https://doi.org/10.1016/j.sna.2017.12.042.
- Andersen, J., 2022. The AR-15 is for mass killing ban it | Opinion. Minessota Reformer. https://minnesotareformer.com/2022/05/31/17232/.
- Anklam III, C., Kirby, A., Sharevski, F., Dietz, P.D., J. e., 2015. Mitigating active shooter impact: analysis for policy options based on agent/computer-based modeling. J. Emergency Manage. 13 (3), 201. https://doi.org/10.5055/jem.2015.0234.
- Arteaga, C., Park, J., 2020. Building design and its effect on evacuation efficiency and casualty levels during an indoor active shooter incident. Saf. Sci. 127, 104692 https://doi.org/10.1016/j.ssci.2020.104692.
- Benitez, G., Caplan, D., Hayden, M. E., & Effron, L. (2016, June 12). Inside the Orlando Nightclub Massacre, Breaking Down the Three Horrific Hours Inside. ABC News. https://abcnews.go.com/US/inside-orlando-nightclub-massacre-breaking-horrific-hours-inside/story?id=39805133.
- Blair, J. P., & Schweit, K. W. (2014). A Study of Active Shooter Incidents in the United States between 2000 and 2013. https://www.fbi.gov/file-repository/active-shooter-study-2000-2013-1.pdf/view.
- Bonabeau, E. (2002). Agent-based modeling: methods and techniques for simulating human systems. Proceedings of the National Academy of Sciences of the United States of America, 99(suppl 3), 7280–7287. https://doi.org/10.1073/pnas.082080899.
- Briggs, T.W., Kennedy, W.G., 2016. Active shooter: An agent-based model of unarmed resistance. 2016 Winter Simulation Conference (WSC), April 2017, 3521–3531. https://doi.org/10.1109/WSC.2016.7822381.
- Browne, M., Jordan, D., Singhvi, A., Cirillo, C., & Fineman, N. (2017, October 21).

 Mapping the Las Vegas Massacre. *New York Times*. https://www.nytimes.com/video/us/10000005473328/las-vegas-shooting-timeline-12-bursts.html.
- Burke, M. (2022, May 18). Tops employees recount horror of Buffalo shooting as some remain determined to reopen for community. NBC News. https://www.nbcnews. com/news/us-news/tops-employees-recount-horror-buffalo-shooting-remaindetermined-reope-rcna29385.
- Cho, C., Park, J., Sakhakarmi, S., 2019. Emergency response: effect of human detection resolution on risks during indoor mass shooting events. Saf. Sci. 114, 160–170. https://doi.org/10.1016/j.ssci.2019.01.021.
- Dezecache, G., Grèzes, J., Dahl, C.D., 2017. The nature and distribution of affiliative behaviour during exposure to mild threat. Roy. Soc. Open Sci. 4 (8) https://doi.org/ 10.1098/rsos.170265.
- Diaz-Gorsi, C. (2021, May 31). Luke AFB Airman saves 28 lives in Westgate shooting. https://www.af.mil/News/Article-Display/Article/2638658/luke-afb-airman-saves-28-lives-in-westgate-shooting/.
- FBI, 2022. Active Shooter Resources: Run. Hide. Fight. https://www.fbi.gov/about/partnerships/office-of-partner-engagement/active-shooter-resources.

- FBI, 2019. Quick Look: 277 Active Shooter Incidents in the United States From 2000 to 2018. https://www.fbi.gov/about/partnerships/office-of-partner-engagement/active-shooter-incidents-graphics.
- Haghani, M., Kuligowski, E., Rajabifard, A., Lentini, P., 2022. Fifty years of scholarly research on terrorism: Intellectual progression, structural composition, trends and knowledge gaps of the field. Int. J. Disaster Risk Reduct. 68, 102714 https://doi.org/ 10.1016/j.iider.2021.102714
- Han, Y., Liu, H., 2017. Modified social force model based on information transmission toward crowd evacuation simulation. Physica A 469, 499–509. https://doi.org/ 10.1016/J.PHYSA.2016.11.014.
- Helbing, D., Molnár, P., 1995. Social force model for pedestrian dynamics. Phys. Rev. E 51 (5), 4282–4286. https://doi.org/10.1103/PhysRevE.51.4282.
- Hou, L., Liu, J.G., Pan, X., Wang, B.H., 2014. A social force evacuation model with the leadership effect. Physica A 400, 93–99. https://doi.org/10.1016/J. PHYSA.2013.12.049.
- Jonson, C.L., Moon, M.M., Hendry, J.A., 2020. One size does not fit all: traditional lockdown versus multioption responses to school shootings. J. School Violence 19 (2), 154–166. https://doi.org/10.1080/15388220.2018.1553719.
- Khodabandelu, A., Park, J., Arteaga, C., 2020. Crane operation planning in overlapping areas through dynamic supply selection. Autom. Constr. 117, 103253 https://doi. org/10.1016/j.autcon.2020.103253.
- Khodabandelu, A., Park, J., 2021. Agent-based modeling and simulation in construction. Autom. Constr. 131, 103882 https://doi.org/10.1016/j.autcon.2021.103882.
- Kram, R., Domingo, A., Ferris, D.P., 1997. Effect of reduced gravity on the preferred walk-run transition speed. J. Exp. Biol. 200 (4).
- Lankford, A., 2019. Confirmation that the United States has six times its global share of public mass shooters, courtesy of Lott and Moody's data. Econ Journal Watch 16 (1), 69
- Lemonik, A., Mikaila, M., 2013. Emergent Norm Theory. In The Wiley-Blackwell Encyclopedia of Social and Political Movements. Blackwell Publishing Ltd. https://doi.org/10.1002/9780470674871.wbespm432.
- Li, Y., Peng, Z., Pal, R., Li, C., 2019. Potential active shooter detection based on radar micro-doppler and range-doppler analysis using artificial neural network. IEEE Sens. J. 19 (3), 1052–1063. https://doi.org/10.1109/JSEN.2018.2879223.
- Lovejoy, C. v., McDonald, M. L., Lucas, T. W., & Sanchez, S. M. (2021). Investigating an Active Shooter Defeat System with Simulation and Data Farming. Proceedings -Winter Simulation Conference, 2021-December. https://doi.org/10.1109/ WSC52266.2021.9715508.
- Lu, X., Astur, R., Gifford, T., 2021. Effects of gunfire location information and guidance on improving survival in virtual mass shooting events. Int. J. Disaster Risk Reduct. 64. 102505 https://doi.org/10.1016/j.jidrr.2021.102505.
- Ma, Y., Yuen, R.K.K., Lee, E.W.M., 2016. Effective leadership for crowd evacuation. Physica A 450, 333–341. https://doi.org/10.1016/J.PHYSA.2015.12.103.
- Masoumi, Z., van L.Genderen, J., & Maleki, J. (2019). Fire Risk Assessment in Dense Urban Areas Using Information Fusion Techniques. ISPRS International Journal of Geo-Information, 8(12), 579. https://doi.org/10.3390/ijgi8120579.
- Mawson, A.R., 2005. Understanding mass panic and other collective responses to threat and disaster. Psychiatry: Interpersonal Biol. Processes 68 (2), 95–113. https://doi. org/10.1521/psyc.2005.68.2.95.
- Metzl, J.M., MacLeish, K.T., 2015. Mental Illness, Mass Shootings, and the Politics of American Firearms. Am. J. Public Health 105 (2), 240–249. https://doi.org/ 10.2105/AJPH.2014.302242.
- Moussaïd, M., Helbing, D., Garnier, S., Johansson, A., Combe, M., Theraulaz, G., 2009. Experimental study of the behavioural mechanisms underlying self-organization in human crowds. Proc. Roy. Soc. B. Biol. Sci. 276 (1668), 2755–2762. https://doi.org/ 10.1098/rspb.2009.0405.

- Muschert, G.W., 2007. Research in school shootings. Sociol. Compass 1 (1), 60–80.News, F.O.X., 2018. February 14). Parkland shooter's movements in school. FOX News, Chilling animation.
- CBS News, 2017, December 8. Sheriff: Substitute teacher, 74, and custodian saved lives in Aztec school shooting. https://www.cbsnews.com/news/sheriff-substitute-teacher-74-and-custodian-saved-lives-in-aztec-school-shooting/.
- NY.GOV, 2010. New York State, Classroom Design Standards. http://www.health.ny.gov/professionals/ems/education/course_sponsors/docs/classroom_design_standards.ndf.
- Parisi, D.R., Dorso, C.O., 2007. Why "Faster is Slower" in Evacuation Process. In: Pedestrian and Evacuation Dynamics 2005 (pp. 341–346). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-47064-9_31.
- Park, J., Arteaga, C., 2019. Human responses of emergency evacuation using agent-based modeling. International Conference on Smart Cities 1–6.
- Pelechano, N., Badler, N.I., 2006. Modeling crowd and trained leader behavior during building evacuation. IEEE Comput. Graphics Appl. 26 (6), 80–86. https://doi.org/ 10.1109/MCG.2006.133.
- Peterson, J., Sackrison, E., Polland, A., 2015. Training students to respond to shootings on campus: is it worth it? J. Threat Assess. Manage. 2 (2), 127–138. https://doi.org/10.1037/tam0000042.
- Qingge, J., Can, G., 2007. Simulating crowd evacuation with a leader-follower model. IJCSES Int. J. Comput. Sci. Eng. Syst. 1 (4).
- SDS, 2018. SDS Shooter Detection Systems. https://shooterdetectionsystems.com.
 Shipman, A., Majumdar, A., 2018. Fear in humans: a glimpse into the crowd-modeling perspective. Transp. Res. Rec. 2672 (1), 183–197. https://doi.org/10.1177/0361198118787343
- Sisk, R., 2019. The Story of Rick Rescorla, Vietnam Vet and 9/11 Hero. https://www.military.com/daily-news/2019/09/13/story-rick-rescorla-vietnam-vet-and-9-11-hero.html
- Smith, A. (2016). Why the AR-15 is the mass shooter's go-to weapon. CNN Money. https://money.cnn.com/2016/06/13/news/ar-15-assault-rifle/index.html.
- Suzuno, K., Tomoeda, A., Ueyama, D., 2013. Analytical investigation of the faster-is-slower effect with a simplified phenomenological model. Phys. Rev. E 88 (5), 052813. https://doi.org/10.1103/PhysRevE.88.052813.
- Templeton, A., Drury, J., Philippides, A., 2018. Walking together: behavioural signatures of psychological crowds. Royal Society Open Science 5 (7). https://doi.org/ 10.1098/rsos.180172.
- Towers, S., Gomez-Lievano, A., Khan, M., Mubayi, A., Castillo-Chavez, C., 2015.

 Contagion in mass killings and school shootings, PLoS ONE 10 (7), e0117259.
- Tucker, M. v., Hemphill, B. O., 2020. Comprehensive Active Shooter Training Program. In Campus Crisis Management (2nd ed., pp. 180–206). Routledge.
- Turner, J.C., Oakes, P.J., Haslam, S.A., McGarty, C., 1994. Self and collective: cognition and social context. Pers. Soc. Psychol. Bull. 20 (5), 454–463. https://doi.org/ 10.1177/0146167294205002.
- Xie, W., Lee, E.W.M., Lee, Y.Y., 2022. Simulation of spontaneous leader-follower behaviour in crowd evacuation. Autom. Constr. 134, 104100 https://doi.org/ 10.1016/J.AUTCON.2021.104100.
- Yang, X., Dong, H., Yao, X., Sun, X., Wang, Q., Zhou, M., 2016. Necessity of guides in pedestrian emergency evacuation. Physica A 442, 397–408. https://doi.org/ 10.1016/J.PHYSA.2015.08.020.
- Zhu, R., Lucas, G.M., Becerik-Gerber, B., Southers, E.G., 2020. Building preparedness in response to active shooter incidents: results of focus group interviews. Int. J. Disaster Risk Reduct. 48, 101617 https://doi.org/10.1016/j.ijdrr.2020.101617.
- Zhu, R., Lucas, G.M., Becerik-Gerber, B., Southers, E.G., Landicho, E., 2022. The impact of security countermeasures on human behavior during active shooter incidents. Sci. Rep. 12 (1), 929. https://doi.org/10.1038/s41598-022-04922-8.