A study of stadium exit design on evacuation performance

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A Study of Stadium Exit Design on Evacuation Performance

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Abstract

The evacuation of a stadium can be a crucial element to consider when designing a stadium. If something goes wrong during an evacuation it can mean the difference between life and death. The following research presents how an evacuation of Ladd Peebles stadium might occur as well as an analysis on the impact of stadium exit dynamics on evacuation performance. Three scenarios were investigated with two sections of the stadium: two unblocked exits, one blocked exit, and one exit that is twice as wide as one of the previous exits. After running the simulation on each of the three scenarios it was found that two unobstructed exits could successfully evacuate Ladd Peebles stadium in less than eight minutes, while one blocked exit could not. It was also determined that having one large exit can reduce the number of congestion points in stadium design and can help to expedite the evacuation process.

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1 Introduction

The safe evacuation of a crowd is a complex operation both in terms of execution and planning. When it is planned, it requires extensive preparation and coordination. When it is not planned, it requires well-designed facilities that can handle the movement of crowds, enable an acceptable and unobstructed rate of egress. Facilities that are not simple and intuitive to navigate contribute to the panic, fear and overall expected psychological burden of an unplanned evacuation. Unfortunately, there have been several historical instances of people were injured and perished during evacuations. Such instances vary in location, time and context. It does not matter if the event is a soccer match in Ghana, Africa that resulted to a deadly stampede killing over 100 people in 2001 [4]; a stampede at a festival celebration killing 456 people and injuring 755 in Phnom Penh, Cambodia [3] or another stampede in 2006 during religious rituals in Mecca, Saudi Arabia that killed 362 and injured at least 289 people [16]. The common thread in all these and hundreds of other incidents throughout history is the lack of safe egress in a crowded space. Buildings, sports complexes and places of religious services are typically designed according to certain construction regulations and code. These regulations mandate the maximum to fit people on the premises and also allow a safe exit in a case of an emergency. It is particularly unfortunate that often the actual cause of the emergency (ex. earthquake, fire, explosion) may be a manageable and not safety-threatening event yet lives may be claimed immediately afterward during a poorly executed evacuation.

Using computer simulation virtual evacuating crowds can be generated and studied under different conditions and physical space configurations [9, 20]. Numerous studies have been performed under different scenarios to understand how physical space constraints and crowd behavior would manifest in a specific environment. Typical tools include evacuation simulation platforms such as EXODUS [5], SIMULEX [18], [19], and FDS+Evac [8].

In this study we examine the impact of exit size and availability during spectator evacuation from a stadium hosting a sporting event. Instead of using an existing evacuation simulation platform we developed our experimentation platform using Unity [21], a multi-platform, video game development engine. By developing an agent-based simulation, we isolated our model to one section of a stadium and were able to simulate scenarios with various types of stadium gate configurations and blockage. Our simulation is based on the physical characteristics of one section at the Ladd Peebles Stadium in Mobile, Alabama.

The remainder of this paper is organized as follows. Section 3 gives a brief background to the area of crowd dynamics in the context of evacuation. The experimentation methodology and simulation are presented in Section 4, and the Results are show in Section 5. The remaining sections discuss the results and provide a conclusion and ideas for future work.

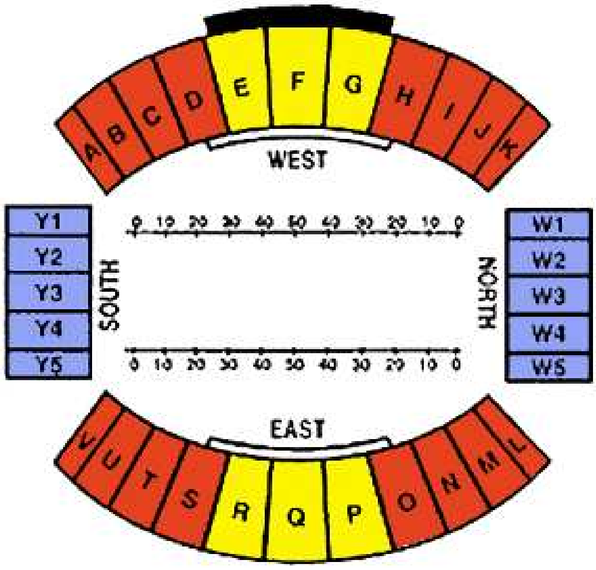

Figure 1: On the left, the seating chart of the Ladd Peebles stadium in Mobile, Alabama, and on the right an actual photograph of the section used to model the environment for the evacuation simulations.

2 Related Work

When designing a stadium, architects and engineers plan how the final structure will accommodate a certain number of spectators. A critical aspect of this planning is also to ensure that stadium infrastructure can support safe and timely evacuation. Some of the design points to consider in the architecture of a stadium include congestion points, exit size and throughput, crowd dynamics, space utilization, level of service, and crowd psychology [12, 15]. International guidelines state that an evacuation of a stadium should take no more than eight minutes, with slight variance depending on the country [10, 17]. The most typical approaches to simulate crowd movement are social forces, rule-based and cellular automata models [12]. Each of these models comes with their own limitations and drawbacks; however none of them are able to effectively replicate the movement of humans in high density crowds. Social force models tend not to respect social rules, rule-based models work well for low densities in normal conditions and cellular automata models limit the movement of the people to a grid-like field. Existing research suggests two main crowd simulation categories, behavioral and movement models [17]. Behavioral models include conceptual models which are based on the analysis of observed and actions of individuals and do not include crowd dynamics. Movement models on the other hand, include a fluid or particle system and are focused on crowd dynamics.

The international standard for a stadium evacuation is eight minutes [10, 15]. This makes the ability to keep traffic flow moving and preventing congestion points an important facet when designing a stadium capable of properly handling an evacuation. There are numerous studies in the literature investigating crowd evacuations and how to improve their efficiency. The common thread in all of these studies is the large number of factors which influence what happens during an evacuation particularly during an emergency at a large public setting such as a sports stadium.

To understand how evacuations take place, it is important to understand both individual behavior and crowd dynamics. One study, for example, found 25% of individuals participating in an evacuation study attempting to convince them to use emergency exits, preferred to evacuate the way they entered a building [7]. One interesting simulation-based study examines each individual in the crowd separately and simulates how they read and react to the environment in different conditions including emergency egress [17]. The work shows that individuals exploit shortcuts when evacuating stadiums, creating congestion, pinching off the crowd flow through the path. One interesting parameter is Fruins Level of Service (LoS) which specifies the safe amount of people which can fit in a specific area. The recommended LoS should be above Level-E (¡ 0.93 m2). However, in a stadium, crowd densities may exceed Fruins recommendations [17]. This affects the safety of the crowd by making the time it takes to evacuate longer, therefore putting the crowd in more danger.

The majority of research into emergency and evacuation situations has been of an empirical nature done by social psychologists and utilized by D. Helbing, B.G. Silverman, and N. Pelechano [6, 10, 11, 15]. An evacuation is a stressful event and once people become stressed, they may lose focus and awareness. They also tend to move faster, become more nervous and may relinquish control of their actions to the group, acting as part of a herd and leading to conformity [6, 10, 15]. This results to everyone moving at the same direction, creating congestion at specific exits while ignoring alternative routes and exits. Congested exits often have adverse cascade effects such as people falling down and becoming obstacles to others attempting to exit, besides the obvious danger of severe injury for them and others.

Given these observations, a number of crowd modeling simulation studies have been conducted to investigate this type of herding behavior and the psychological factors at play 6, 10, 11, 15. In such simulations, evacuees are represented as agents, each with a list of goals, interests, emotions, leadership traits, and positive or negative relationships with other agents. The traits of each agent determine its grouping and polarization effects based on the scenario [11]. The simulation results tend to show flocking behavior by forming groups with similar parameters and interest points. For example, at an art exhibit, the group moves between exhibits of common interest; at a stadium evacuation, the group moves towards an exit. Coupling this behavior with movement, individual agents can be implemented using generic collision detection algorithms to avoid collisions in crowd movement. Based on an agent's velocity, collisions can be resolved by either slowing down or stopping agents. Even better, as individual agent goals are known, the direction of their movement can be modified to prevent a future collision and then reevaluate their route once the collision threat has passed [11].

It is therefore necessary to model behaviors and movement tendencies. However, the current trend in crowd simulation dynamics is to use social forces, rule-based and cellular automata models which cannot realistically animate high density crowds [12]. Models must incorporate a variety of other factors such as locomotion, path planning, navigation in large virtual environments, and realistic behavior simulation using cognitive models [13]. One suggested model determines the attractor point (goal location) that each agent walks to, or in a stadium evacuation what exit each person should take [13]. Then each agent proceeds towards the exit avoid collisions with static and moving obstacles. Agents must also stop when movement without collision is impossible -unless they are pushed. This is a realistic expectation in an emergency evacuation and cures the effect known as shaking that occurs with high density crowds. Shaking is where the crowds begin to appear as if they are vibrating rapidly when caught in a bottleneck.

Another suggested approach is to develop psycho-socio-physio-logical models to reveal the impact of environment on simulation agents. Such models would include factors that affect the agents ability to reach its goal (ex. navigation) along with the incorporation of a set of other elements such as knowledge of the floor plan, stress, emotions and prior training or experience with a similar situation 15.

A common concern in a simulated environment is also the fidelity and precision of the selected population for the simulation. This is mitigated with the use of stochastic models (Monte Carlo techniques) that ensure the precise composition of a population and randomly change between simulation runs 7. Yet the validity of crowd simulation results can be difficult to validate when evacuating large groups. Overly optimistic results may have lethal effects in a case of a real emergency while decisions based on pessimistic results may be costly in terms of unnecessary infrastructure improvements.

Overall, understanding and incorporating the factors which affect crowd dynamics, psychology, and their interaction in a stadium, an evacuation simulation can be made more accurate and reliable. Software simulations should be used as an extension of a drill and should not be the deciding influence on implementation of stadium designs and policies 7.

3 Methodology

The stadium chosen as the model for our study is Ladd Peebles stadium in Mobile Alabama. Ladd Peebles was built in 1948 has a maximum capacity of 33,471 spectators [1]. It is a single-floor, outdoor football stadium with 28 section of bleachers all around its perimeter. The two large sides contain ten exits and the two smaller sides contain four exits each, with the number of sections matching the number of exits on every side. We selected this stadium because of its structural simplicity such as the lack of multiple levels and having exits that lead directly out of the stadium. We isolated one of the short-ends as the focus of the model, namely two sections with two exits (Figure 1B). For the experimentation, a 3D modeling tool was used to recreate the two stadium sections and a game engine to implement path finding and collision detection algorithms [2, 21].

To keep the model as close to the real stadium, a number of computations were made to accurately estimate and scale the two sections. According to previous crowd dynamics studies, the average person size can be estimated to have a breadth of 51.50 cm and depth of 29.00 cm [17]. Ladd Peebles stadium has a maximum capacity of 33,471 for 28 sections so the maximum capacity of the two sections should not exceed 2,391 spectators. With this in mind, each individual spectator agents were scaled in size accordingly, allowing up to 2,391 agents filling up the stands. Another variable in the model is the movement velocity of the agents. Still suggests that, for safety, the maximum flow through an exit is 109 people per meter width per minute 17. With exits 1.5 m wide, the max speed of each person going through an exit should be 2.725 people per second. The speed of the agents was modeled to match this flow rate. Fruins Level of Service recommended values were also adjusted so that the collision radius of each agent was adjusted to not be just at Level-E (¡ 0.93 m2), while recognizing that crowd densities in in a stadium situation may surpass Level-E and even reach Level-F levels of service. For each one of the experimentation scenarios, the agents were randomly placed throughout the stadium.

To test the traffic flow, three operational scenarios were devised (Table 1). The first two scenarios used the physical characteristics of the Ladd Peebles stadium design, having one exit per section. The only variation in the second scenario was the intentional blocking of the one exit to see the effects of forcing spectators through a single exit. The last scenario maintained the single exit but doubled its width, therefore offering a single exit equivalent in terms of the opening width to the size of the two exits of the physical stadium.

Table 1: The three operational scenarios examined during the simulation study. For the first two scenarios (A, B) had different number of exits while the last scenario (C) used a different exit size.

Scenario	# of Sections	# of Exits
A	2	2
B	2	1
C	2	1 (double wide)

4 Experimental Results

The results from the evacuation simulation were obtained from runs of 1,000 agents at a 1.0 timescale. Ten runs were performed on each of the three scenarios. The data being recorded is the flow rate of each waypoint, which is outside of each of the exits, and the time elapsed before all one thousand agents reached these waypoints. The evacuation time ranged from 300 seconds at the fastest on the single large exit scene, to 500 seconds at the slowest in a single small exit (Appendix 1). When simulated with one exit blocked and the other at normal size, agents we able to evacuate in a mean of 465.9 seconds and the standard deviation of this simulation was 24.37 (Table 2). This was significantly higher than the two exit simulation which had a mean of 401.7 seconds and a standard deviation of 21.94. However, the one exit of larger size produced a lower mean of 330.4 seconds and a standard deviation of 17.41. The substantial size of the standard deviation was caused by the fact that the agents are spawned randomly in the stadium when the simulation is loaded. This means that since people can sit in random seats in a stadium, the amount of time each evacuation scenario will take can vary based on their distance from the exits at the beginning of the evacuation.

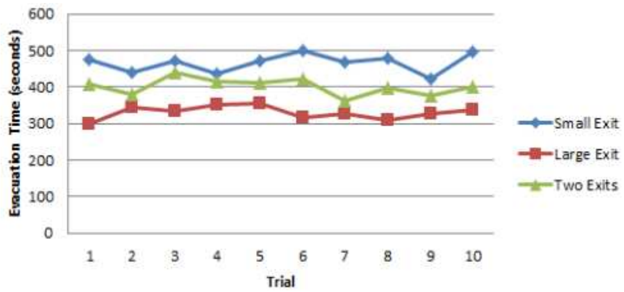

Figure 2: Evacuation time comparison (sec) for each scenario.

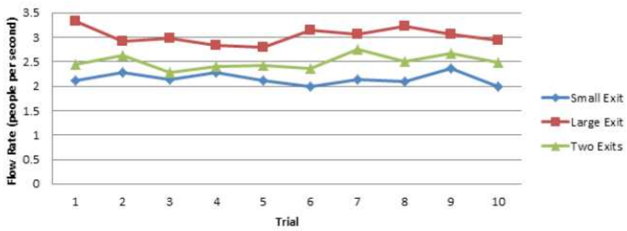

Figure 3: Flow rate comparison (people/sec) for each scenario.

All of the agents made it out of the stadium within the 8 minute time constraint in every scene except for two trials. Trials 6 and 10 in the single small exit attempts were over the 8 minutes, or 480 seconds, which results in a failed evacuation by Stills standards [17]. Overall, the evacuations of the small blocked exit were significantly longer than the two and one large exit trials. Flow rate seems to have an inverse relationship with evacuation times; the higher the flow rate, the less time it takes for people to evacuate the stadium (Figures 2 and 3). The small exit had the lowest total flow rate, and also

Table 2: Statistical data for evacuation time and flow rate of large and small single exits.

	Evacuation Time (sec)			Evacuation Flow Rate (people/sec)		
Number of Exits	Two	One	One (double width)	Two	One	One (double width)
Mean	401.7	465.9	330.4	2.495	2.15	3.029
Median	405.5	470.0	331	2.465	2.125	3.02
Range	77	79	57	0.47	0.37	0.53
Standard Deviation	21.936	24.369	17.413	0.136	0.114	0.160

took the longest time to evacuate the agents due to less people getting through the gates per second.

5 Conclusion and Future Work

In an emergency evacuation, every second counts. The first result shows an expected outcome, that if one of the two exits becomes blocked, the evacuation time is higher, by an average of 64.2 seconds and the total flow rate is on average 0.35 people per second slower. The average evacuation time of one blocked exit is 465.9 seconds (7.765 minutes) which is under the required eight minute mark. However, during our simulation trials, in one trial evacuation came a second short of the mark and in two other occasions passed it.

The more interesting outcomes though came during the single, wider exit simulations. The results show that the single, double-width exit configuration for two sections is much more efficient than the two exit configuration. The single larger exit has a higher flow rate and allows in some cases the evacuation of as quickly as 101 seconds faster while maintaining a flow rate that is more than double the two exit configuration.

The may be a reasonable n explanation as to why a single larger exit is more efficient than the two normal-sized exits. During an evacuation, people tend to flock and create congestion points, typically one on each side, of an exit. By reducing the number of exits, the, number of congestion points is also reduced, effectively by 50%. .The extended width of the exit also helps in relieving the congestion levels by letting more people flow though. . By the time the other half of the section which would have been served by their own exit reaches the only open exit, the congestion points are less congested, therefore allowing a smooth out-flow. .

The simulation showed a decrease in the level of service of individuals in the larger exits due to the increased number of people attempting to use it. This means that more agents tried to fit into the exit, which follows the psychological effects that would occur if there was only one exit in an emergency evacuation. In fact, one extra person will on occasion manage to squeeze onto the exit steps, equating to seven agents walking through the exit at a time rather than three per exit when there are two exits. The model and simulation based on two sections of the Ladd Peebles stadium provided numerous insights about spectator capacity, stadium design and evacuation procedures. Our simulation results indicate that having one exit is not enough to safely evacuate spectators from two sections of the Ladd Peebles stadium. While only one simulated trial exceeded the safety requirement for evacuation in eight minutes, the rest of the trials averaged just 14 seconds below it. Considering that each trial used 1,000 spectators instead of the maximum capacity of 2,391, the likelihood a safe evacuation can be carried out when the stadium is full, is very low. Further parameter modifications were able to investigate operational scenarios under different exit configurations. Examining exit width instead of just quantity (number of exits) yielded some interesting results. With spectator safety as the only requirement, the models showed that wider exits resulted in much quicker evacuations, even when the number of exits was cut in half. Clearly, a combination of the two ideas, a greater number of wider exists would be ideal. But such decisions, as long as they don't jeopardize safety, need to be also balanced against stadium capacity requirements that may in-turn directly affect ticket sales. Instead of one or the other, creating two larger exits would be to the benefit of everyone except for ticket sales as more seats would be removed for the increased exit size. There are also many ways to improve our model and simulation. We used a generic agent for every spectator which is an oversimplification. A more physiologically diverse agent population such as agents of various heights, ages and weights would make the simulation more realistic. Including psychological and behavioral features would significantly enhance the fidelity of the model. For example, enabling agents to panic and act erratically if one of the exits suddenly becomes blocked. Such behavior could result in agents falling or pushing others down, increasing the number and size of any congestion points in the evacuation path.

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Table 3: Statistical data for evacuation time and flow rate of large and small single exits.

Trials \ Number of Exits	Evacuation Time (sec) Two	One	One (double width)	Evacuation Flow Rate (people/sec) Two	One	One (double width)
1	409	474	300	2.44	2.11	3.33
2	381	440	344	2.62	2.27	2.91
3	440	470	335	2.28	2.13	2.98
4	414	438	351	2.41	2.28	2.84
5	411	470	357	2.43	2.12	2.80
6	423	500	316	2.36	2.00	3.15
7	363	469	327	2.75	2.13	3.06
8	398	479	309	2.51	2.09	3.22
9	376	421	326	2.66	2.37	3.06
10	402	498	339	2.49	2.00	2.94
Average	401.7	465.9	330.4	2.495	2.15	3.029

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