Variability in Stadia Evacuation under Normal, High-Motivation, and Emergency Egress

As published in the Journal of Building Engineering

August 2021, https://doi.org/10.1016/j.jobe.2021.102361

(Manuscript Author order: Timothy Young, John Gales, Michael Kinsey, and William C-K Wong)

John Gales PhD (Principal Investigator, York University)
Timothy Young (Research Student, York University
Michael Kinsey (Arup)
William C-K Wong (Arup)

Abstract

Egress modelling can be used in stadia design. This modelling describes the movement of pedestrians and crowd flow considering wayfinding and decision making in evacuation and circulation. The accuracy of the modelling is highly dependent on project-specific input data that accurately represents the movement of population with associated human factors considered. Currently, there are few contemporary studies of stadia that consider real egress decision making under a range of stimuli of which practitioners may use to influence their modelling and design process. Herein, a range of evacuation urgencies and their effect on pedestrian decision making and wayfinding in stadia are considered: standard post-game egress, egress under high-motivation conditions, and emergency egress. This is done through carefully collected and recorded observation of real stadia in Canada and obtained third party video for stadiums internationally. To reinforce findings, real case studies of other notable emergencies are also considered. Decision making at all stages of evacuation are analyzed. Results indicate that, based on the cases examined, the egress behaviours differ in relation to the level of urgency, such as high motivation and emergency, and gate densities are higher for high motivation egress by a factor of 1.5. The role of staff in the evacuation process is one of the predominant factors in reducing or extending premovement regardless of the scenario. Associated contemporary behavioural theorems are used to explain differences in movement and decision-making in evacuation scenarios.

Keywords:

Human factors; response patterns; egress; hazard evaluation; decision making;

Table of Contents

1. Introduction & Motivation 1
2. Background 1
2.1. Crowd Flow Considerations in Design 3
2.2. Consideration of Human Behaviour in Pedestrian Modelling 4
2.3. Contemporary Behavioural Frameworks 6
3. Methodology 7
3.1. Tennis Stadium – Standard and High-Motivation (Rain) Egress 8
3.2. Canadian Football Stadium – Emergency (Fire) Egress 11
3.3. Study Limitations 12
4. Behavioural Observations 13
4.1. Standard Post-Game and High-Motivation (Rainfall) Egress Studies 13
  4.1.1. Queuing and Congestion 17
  4.1.2. Wayfinding 20
4.2. Emergency (Fire) Egress Study 22
  4.2.1. Canadian Football Stadium Fire 22
  4.2.2. Pyrotechnic Machine Fire at Nissan Stadium 24
  4.2.3. Bradford City Stadium Fire 26
4.3. Observed Similarities and Differences between Studies 27
5. Future Research 29
5.1. Recommendations for Future Studies 29
5.2. Recommendations for Future Evacuation Modelling 30
6. Conclusions 31
7. Acknowledgments 32
8. References 33

1. Introduction & Motivation

Accurately representing pedestrian behaviour and movement is of critical importance in the design process of stadia, particularly in the case of emergency evacuations (fire, terrorism, etc.). To accurately create an evacuation model of an emergency egress, the complex field of human behaviour must be incorporated. Currently, there are few documented studies where stadia movement is quantified that may be used for validation modelling to assist design. Additionally, the current understanding of human behaviour in terms of decision making and way finding is lacking. This can limit resulting model configurations with uncertainties, biases, assumptions and generalizations. The research herein is a continuation of previous studies which considered the quantification of movement speeds for modelling egresses of Canadian stadia [1].

The purpose of this first-stage study is to determine and reveal differences in egress behaviours under various circumstances to aid in producing refined modelling inputs and parameters for future validation and verification of stadia. While movement speed data is critical in the modelling process, this has been addressed elsewhere and is not the current paper's focus. Instead, this paper focuses on the various behavioural factors to be considered during a stadia evacuation. The scenarios herein include a normal egress (post game), a high motivation (rain downpour) evacuation, and an emergency (fire) induced evacuation in Canadian stadia. Two additional emergency evacuation case studies of stadia (one historical and one contemporary) were considered to confirm the behavioural actions observed in the emergency scenario.

The combined results of the studies in this paper go beyond congestion and movement speed analysis to compare and highlight the differences in the behaviour of stadium spectators under different situational parameters, using the modern behavioural theories. The focus of this study places emphasis on emergency evacuations, investigating how the type of stimuli and threat perception may affect a person's response to the cues to leave and their behaviour in the process of evacuation afterwards [2]. This study also aims to highlight the significance of the role of staff and authority on the stadium evacuation process. The behaviours observed herein are explained through behavioural and decision-making models. Although limited theories were used, we acknowledge that additional behavioural frameworks could also be considered in future analyses to build upon this foundational research. Due to the rarity of real urgent and emergency egresses, only one trial for each scenario was recorded and analyzed. The authors acknowledge that the information collected for this study is limited and more data is needed to confirm the behaviours and effects observed. Although limited to the specific scenarios and locations considered, this study suggests potential useful considerations when tailoring future evacuation models that incorporate more defined behavioural actions and for the management of stadium evacuation.

2. Background

Stadia design presents unique challenges to accommodate not only large crowd sizes, but full evacuations of these crowds during regular egress and high motivation and emergency scenarios.

From 1961-1971, multiple incidents resulting in pedestrian injury recurred at Ibrox Park in Glasgow due to unsafe measures in a stairwell, contributing to 68 casualties and 219 injuries total. These events led to a report by Scientific Control Systems (Commonly referred to as the SCICON report) [3] and subsequent Green Guide documents which revolutionized stadia design in the years that followed. Examination of stadium disaster case studies from 1981 to 2017 (see Table 1) illustrate that stadia still require additional research and standard development that involve an understanding of associated human factors to minimize injury during evacuation. The various range of stadia incidents demonstrate the large role of pedestrian motion for the range of scenarios of emergencies, as most disasters were due to crowd movement. The purpose of the table is to define the scenarios and country to consider cultural effects and scenario-specific data. Details of the involved pedestrians and population in attendance has not been provided as the data is unreliable.

Table 1. Selected Stadium Incidents

Year	Stadium	Country	Capacity	Disaster	Casualties	Injuries
1981	Karaiskakis Stadium	Greece	32,115	Crowd Crush	24	N/A
1982	Estadio Olimpico	Colombia	72,698	Crowd Crush	21	55
1982	Luzhniki Stadium	Russia	81,000	Crowd Crush	66	61
1985	King Baudouin Stadium	Belgium	50,093	Riot	39	600
1985	Bradford Stadium	England	25,136	Fire	52	265
1987	Tripoli International Stadium	Libya	65,000	Structural	20	N/A
1988	Dasarath Rangasala Stadium	Nepal	15,992	Crowd Crush	93	100
1989	Hillsborough Stadium	England	39,732	Crowd Crush	96	766
1991	Oppenheimer Stadium	South Africa	23,000	Crowd Crush	71	N/A
1992	Armand Cesari Stadium	France	16,078	Structural	18	N/A
1996	Independence Stadium	Zambia	30,000	Crowd Crush	9	78
1996	Tripoli International Stadium	Libya	65,000	Riot	50	N/A

1996	Mateo Flores National Stadium	Guatemala	26,000	Crowd Crush	80	147
2000	Samuel Kanyon Doe Sports Complex	Liberia	50,000	Crowd Crush	3	N/A
2000	Harare Stadium	Zimbawe	80,000	Crowd Crush	13	N/A
2001	Stade TP Mazembe	Congo	18,500	Crowd Crush	8	N/A
2001	Vatani Stadium	Iran	15,000	Structural	3	N/A
2001	Accra Sports' Stadium	Ghana	40,000	Riot, Crowd Crush	126	N/A
2001	Ellis Park Stadium	South Africa	62,567	Crowd Crush	43	51
2009	Le Felicia	Ivory Coast	50,000	Crowd Crush	22	N/A
2012	Port Said Stadium	Egypt	18,000	Riot	74	1000
2013	Le Felicia	Ivory Coast	50,000	Crowd Crush	61	200
2017	Manchester Arena	England	14,200	Terrorism	22	800

2.1. Crowd Flow Considerations in Design

Crowd management was examined significantly in 1972 by SCICON [3], with the aim of "*developing [a] method of assessment for establishing the design characteristics for safe movement, accommodation and control within football stadium and its immediate environment*" [3]. Through a series of stadium studies in the UK, those authors described that when evacuations surpass 7-minutes, crowd pressure becomes severe, flow becomes turbulent, and evacuees display visible signs of anxiety. As a result, those authors believed that after 7 minutes, individuals may lose control over their own movement. These findings are what formularized as the 8-minute rule [4] and has since been used as the criterion basis for calculating capacities of exit routes in many global jurisdictions. Two later studies performed on Canadian stadia in 1977 [5] and 1982 [6] with evacuation times greater than 8 minutes found inconsistencies with this guideline. These studies raised important arguments suggesting that the accepted egress estimates for crowd flow were unrealistic and standards of safety were not explicitly established nor well understood.

It is also important to remark that many of the studies that followed in North America influenced different prescriptive requirements. In North America, the National Fire Protection Association (NFPA) 101 Life Safety Code is used to determine egress standards for stadia [7]. Stadiums designed under NFPA 101 must conform to maximum permitted travel distances to exits, which limits the stadium's overall evacuation time. Similar to SCICON's 8-minute rule, NFPA 101 also has regulations requiring that the design will allow people to egress from the stands to reach an egress concourse within a nominal flow time. However, instead of a single value, NFPA 101 uses a linear relationship to determine the nominal flow time based on the number of seats. This ranges from 3.3 minutes for a 2000 seat stadium up to a maximum of 11 minutes for a 25000+ seat stadium. This nominal flow time refers to the minimum flow time for the most able population; some less able spectators or spectators unfamiliar with the environment may take longer. Because these approaches were based on studies that were completed prior to the development of computational tools, they lack quantitative results required for modern modelling applications, as well as available raw data to further advance theories of the associated human behaviour.

2.2. Consideration of Human Behaviour in Pedestrian Modelling

A review study by Meacham in 1999 [8] found that the initial prescriptive-based regulations have led fire safety engineers to potentially be unaccustomed to fully considering human behaviour and response factors within evacuations. With the transition towards performance-based design, an increased understanding of human behaviour and response issues are needed for fire safety management plans. It should be considered that delays are inherent in human response to an emergency, which translates to delays prior to evacuation commencement, delays during evacuation and the potential for some people to not evacuate on their own. Meachan also suggested that modelling must work towards incorporating a more thorough understanding of human behaviour [8]. Harney [9] follows by providing a more in-depth review of crowd modelling approaches. Harney's analysis of agent-based modelling as an emerging technology proved it to be a promising approach that can aid in providing realistic microscopic analyses. Here, agents possess intelligence and adaptability and thus have the ability to pursue independent action and interact with other agents. In the study, a variety of approaches are compared to understand what methods are successful and accurate. These approaches include a multitude of both microscopic models, in which the data focuses specifically on individual pedestrians, and macroscopic perspectives. In this, the crowd is looked at as a system rather than individual agents. Harney concludes that the models can be applied to large-scale problems [9]. However, their effectiveness is reliant upon available movement data and well-developed theories to predict the way people move, either as part of a software's inherent algorithm or through user inputs. Harney notes that because pedestrians are constantly interacting with their environment and others changing their movement accordingly, it is more difficult to capture data which encompasses their behaviour. The limited availability of movement information within detailed scenarios emphasizes the need for egress studies to provide validation for simulation models, since the reliability of these egress models in performance-based stadium design is dependent on the confidence of the input data.

There are several potential empirical methods for examining crowd behaviour and motion, as summarized by Haghani and Sarvi in 2018 [10]. The methods summarized exist on a continuum between laboratory and field in nature. More lab experiments may involve human or animal subjects in controlled lab environments, VR, or hypothetical-choice scenarios. Other methods such as analysis of natural walking, and analysis of natural disasters are more on the field end of the spectrum. Evacuation drills and post-disaster interviews are in the middle of this spectrum. Lab studies were found to have more control over variation and responses, and as such were more replicable. However, these studies lacked contextual realism and environmental realism. As the studies become more field-like in nature, they become more realistic with observed decisions and behaviours made in response to real-life situations within a more natural environment. However, this removes significant amounts of control over variation and responses. As such, these studies are harder to replicate, with a potentially low number of possible repetitions.

Fire drills are shown by Haghani and Sarvi to be a middle ground, with moderate levels of environmental realism and replicability. However, they also have their drawbacks as well. Gwynne et. al. [11] examined the strengths and limitations of fire drills relative to other egress methods for assessing evacuation performance. One of the key challenges with the use of drills is that inducing additional factors to drills representing more restrictive or urgent scenarios may expose evacuees to potential injury, stress, anxiety, and potentially crush situations. As such, these more urgent factors cannot be added to drills despite adding to the realism and credibility of conditions faced. Another challenge is that it may be difficult to place instruments within the building to collect sufficient data without influencing the outcome from occupants seeing the cameras and staff. Alternative methods for determining egress training and assessment are also compared, including use of simulation tools, lab experiments, and VR. Many techniques such as information sessions, post-evacuation debriefing, and mental rehearsals are more aimed at training and evaluating egress outside of actual drill/emergency environments and are proposed as complimentary tools for measuring the effectiveness of evacuations.

Each method has its own merits and drawbacks, but for maximum realism and examination of realistic environmental effects, field analysis of behaviour is needed. It should be noted that these studies are thus less replicable and harder to extract data from, especially when analyzing motion or movement speeds.

Considering the challenges of field analysis, knowledge and understanding regarding how people move and anthropometric data is currently limited. Fruin profiles of movement [12], for example, are presented independently of the demographic for which they were derived from. This method applies a nominal distribution of a single walker speed from a general circulation study to represent movement, which is used to randomly assign a speed for all agents [12]. Careful examination of different studies reveals that movement profiles can be approximations of the overall population and are loosely based on the collected movement and behaviour data. The Ando movement profile [13] is an example of this. When translating this highly cited paper, it was found that explanation regarding methodology and collection methods of the movement data lacks details [13]. Similar issues are present with the studies performed by Pauls [5, 6, 14]. Pauls' studies would appear to be particularly interesting in relation to this study as they are also performed at Canadian stadia like those of the authors. However, those studies predate the widespread use of computer-based pedestrian modelling and digitized data collection, and thus the final findings lack the necessary detail for modelling software input parameters.

More recently, the authors have begun to compile input data pertaining to movement speeds and anthropometry. While these have been preliminarily introduced elsewhere by the authors in another publication [15], that study's scope did not detail the human factors or decision making that influences egress. A recent study by Larsson et al. [16] was conducted to update movement statistics with contemporary data. Those authors produced quantitative data on the relationships between crowd flow, density, and velocity for the following four events at a multi-use stadium in England: football, rugby, a male music performer, and a female music performer. Density was demonstrated to be inversely related to the velocity and flow. As well, the density of the crowd will often be the dictating factor of the velocity and flow. For example, a decrease in density will increase flow and velocity as the crowd can move more easily. On the contrary, an increase in density will decrease the flow and velocity. The study then produced population densities, flowrates and velocities which had all fell below those typically assumed by the Green Guide [4], thus confirming the need to continually update engineering tools (data and methods) with contemporary results, and further analyze the underlying factors that define these results. Through the comparison of the four events, the authors were able to qualitatively attribute limited factors to the observed variances in crowd flow, density, and velocity. The interactions within the crowd were believed to be affected by the following physical and social parameters of the different demographics: population density, body footprints, walking speeds, group size and cohesion, and other situational parameters (e.g. time of day, time of year, and whether the team won or lost) [16]. That analysis, however, did not consider human factors or external stimuli to evacuation, and instead called for continued studies to give more detailed attention to the underlying conditions that can explain the differences between demographic compositions, group behaviours and the resulting impact on egress.

2.3. Contemporary Behavioural Frameworks

Haghani and Sarvi [10] also indicate that accurate and reliable models need to accommodate psychological and behavioural phenomena, which they categorized as strategic-level ("What-to-do"), tactical-level ("Where-to-go"), and operational-level ("How-to-get-there"). They also indicate potential topics for further research including roles of stress and time pressure on egress decision-making, considering the nature of individual differences in perception and responses.

Decisional frameworks such as the Protective Action Decision Model (PADM) [17, 18] could be considered to examine decision making stages in emergency egress situations. This model is based on the research of people's responses to environmental hazards and disasters – it attempts to describe the pre-decisional and decisional sequence of action making. The PADM framework, however, remains a hypothetical provisional framework that is yet to be validated with application to emergency-based evacuation scenarios. A review study by Kuligowski in 2013 [19] analyzed the present methods to attempt to incorporate occupant behaviour in modelling with simplified behavioural processes. It was found that users could assign periods of delay to occupants to represent pre-evacuation period, and sequences of actions to simulate interruptions to continuous movement. These approaches, however, rely on the user's inputs in which there is limited available guidance, comprehensive dataset, and behaviour theories to reliably predict behaviour [19].

To promote the consideration of behavioural components in evacuee modelling, emerging studies have compiled a set of behavioral statements of key behaviors that people exhibit during an evacuation [20]. Other studies have highlighted that such decision making within the evacuation process can be suboptimal and/or result in mistakes being made caused by cognitive biases [21, 22]. In these studies and video analyses, it is important that caution be undertaken to reduce the subjectivity of looking for specific actions, where new actions may also be observed. It is acknowledged by the authors herein that there are multiple behavioural frameworks (with some emerging such as social identities for example [23]) that could be considered to describe egress. To further explore the egress process herein, we have focused our attention to behavioural heuristics such as cognitive biases. Biases have the potential to affect a person's decision-making process, primarily by delaying/ or hurrying the decision to evacuate. However, to truly validate their presence and significance, surveys with those who egressed are needed, otherwise definition is too subjective. In that sense, the behaviours classified herein will not encompass all possible occurrences.

3. Methodology

The following tables describe information of the events which were investigated by the authors. Table 2 lists the primary studies of this paper. Table 3 lists the supporting studies that are later used to interrogate observations. Further details on the stadia, events, methods of data collection and analysis, and conditions of egress are outlined within the subsequent sections. All studies were analyzed individually by three members of the authors' research team and results later compared to reduce subjectivity of visual observations. The footage from these videos allowed for the generation of a timeline to determine and reveal key events during each egress and quantify re-occurring behaviours. The timelines listing observed patron behaviours are a compilation of observations by the authors, most of which were verified to be the same across all three researchers with the exception of a few people for individual behaviours. Where a disagreement or ambiguity existed, the footage was reviewed by the three researchers to confirm or reject the observation. Flow counts were also performed at the exits by counting the number of patrons passing through at approximately 5-second intervals and were added into the timeline after the flows were determined. This was the same procedure used to count exit use proportions for way-finding.

Similar protocols to the rain and standard egress scenarios were used to generate the observations for the fire scenarios. However, no flow data was collected due to the inconsistent camera angles and footage.

Table 2. Egress Scenarios Collected and Studied by the Authors

Event	Filming Date	Attendance who egressed	Egress Type
Tennis Stadium	2019	12,000	Normal (Post-Game)
Tennis Stadium	2019	2,000	High-Motivation (Rainfall)
Football Stadium	2018	128 (one stand)	Emergency (Fire)

Table 3. Comparative Events Considered from Existing Literature

Stadium	Location	Date	Event	Attendance	Egress Type
Nissan Stadium	Nashville, USA	September 15, 2019	National Football	62,849	Emergency (Fire)
Bradford Stadium	Bradford, UK	May 11, 1985	English League Football	11,076	Emergency (Fire)

3.1. Tennis Stadium – Standard and High-Motivation (Rain) Egress

This stadium is a fifteen-acre multipurpose sport and entertainment complex integrated into York University in Toronto, Ontario. It regularly hosts professional tennis tournaments each summer. According to CAD floorplans of the stadium, each gate is 2.54 meters wide at its entrance, which is the narrowest point, and the walkways leading to these exits are each 2.89 meters wide. As the stadium is highly symmetric, these measurements are the same for all 8 gates and the perimeter walkways leading to them. These CAD plans have been reproduced in a simplified manner and are provided with the pertinent dimensions below in Figure 1. A seven-day event was selected to conduct multiple data collection studies, some of which are beyond the current scope of this paper (movement speeds for example). Filming required the rotation of six researchers of the York University Fire research group. Stadium film access was granted by the university, and spectators were informed of filming and photography taking place. The methodology and data collection procedure had been inspired by methodologies described by Pauls et al. [14]. For the focus of this study, the authors set-up equipment to record and analyze human behaviour in the main stadium. During this tournament, spectator access to the upper deck was not permitted, allowing for the research team to set-up unimpeded panoramic views of the stadium bowl and grounds. A series of GoPro 7s (1080p HD resolution) were stationed at two carefully selected vantage points, as displayed in Figure 2 with their respective fields of view. Figure 3 shows a sample still photo taken from the video footage. Both Standard and High Motivation egress events used the same filming methodologies.

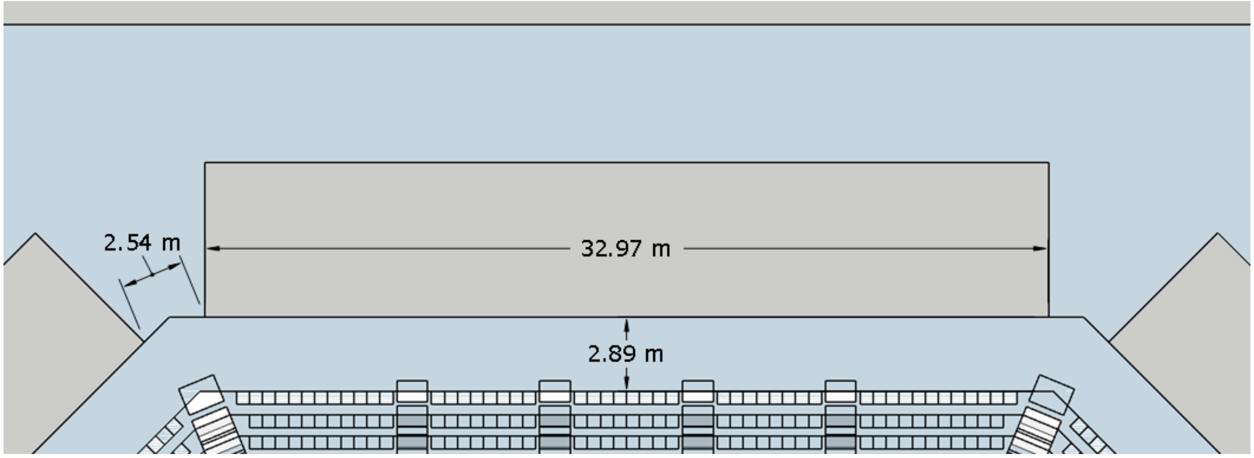

Figure 1. Dimensions of walkways and gates, taken from proprietary CAD drawings of York University Stadium

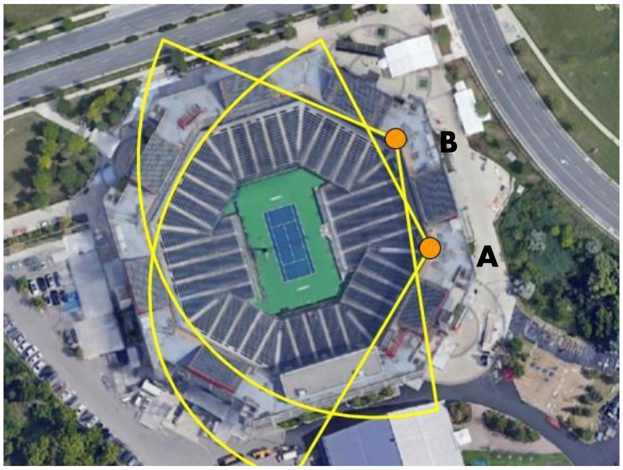

Figure 2. Tennis Stadium at York University camera stations and approximate field of view.

Figure 3. Still image of a utilized Centre Court camera illustrating an observed gate.

Filming was continuous from opening of the stadium to the second to last match. The highest attended match would be the second last every night and this was predominately at full capacity. The attendance rate of the unfilmed last match of the night would often be about 20% capacity.

With the objective of capturing an emergency egress, artificially induced events such as fire drills were prohibited from an ethical and scheduling standpoint by the university. However, for high motivation egress filming, the authors considered adverse weather conditions as the stadium is open to elements with no overhead shelter with exception of the stadium concourse. The authors therefore had to time filming with a sporting match in progress and a downpour of rain significant enough to end the match. It was critical that rain occurred suddenly, as the match would then be suspended, and a full evacuation of the stadium bowl would then take part as there is no shelter from rain. Sudden rain events in tennis suspend play, whereas periodic rain will not suspend play. The procedure when play is suspended is to evacuate the stadium bowl and the spectators can then take shelter. It should be noted that not all sports will follow this procedure; in Canadian football for example, play will not stop when rain occurs and is continuous.

Filming was continuous for the duration of the seven-day tournament, in which one rainfall event was observed. The authors recorded an afternoon rainfall event and observed an egress of approximately 2000 spectators for that event (this is an expected attendance that is often seen in afternoon matches). No other rain events occurred in that tournament. The entire stadium was recorded with two gates filmed at close range. This permitted further observations to compare to other scenarios and stress states, and congestion. It was not possible to survey the spectators of the stadium afterwards as this was beyond the ethical clearance granted to the authors. Therefore, the authors are reserved in quantifying specific types of behaviours where subjectivity is present.

In both scenarios, Gates B and C (at the location of cameras A and B, respectively) were used to record the amount of people arriving at and departing from the gate every five seconds during the egress. The data from the camera footage was then used to develop graphical interpretations of the egress: the percent of the population egressed with time, and the flow of people per unit width of the gate with time. Additionally, records were taken to track exit usage by assigning the chosen exit to each spectator. These results are coupled with qualitative interpretations and behaviour descriptors as discussed in Section 4.1.

3.2. Canadian Football Stadium – Emergency (Fire) Egress

The fire egress study was taken as a case study regarding the behavioural aspects of stadium spectators during an emergency. This case study reviews the event of a localized fire at a Canadian Football stadium (the same as noted in [1] but recorded by third party spectators). The stadium itself did not have available footage of the event, nor did the authors have high-resolution cameras permanently installed on-site (the authors research team has had ongoing filming studies here since 2017). Therefore, this study is limited to footage recorded (7 short films) and shared by spectators to the authors. The vast majority of fans were in the south stands, with some fans of the opposing team in the lowest section of the north stands, highlighted in the figure below. There were no people in the upper section of the north stands. The focus of the behavioural study herein was on the localized stand area (refer to Figure 4) as clear footage for the adjacent stands was not publicly available.

Figure 4. Canadian Football Stadium aerial view (incident stand highlighted) (left) and still image of publicly posted footage captured by spectators at the event (right)

A few fans of the opposing team lit flares and other incendiary devices, which resulted in a small explosion and set their banner on fire. The incident occurred in the second half of the match, and the opposing team was winning by one point when the fire occurred. The fans who were actively involved in the lighting of flares were identified as 'masked individuals' as they were seen wearing masks during the incident. At the beginning of the footage, the stands where the fire took place was at approximately 20% of the capacity, with 32 people present. The adjacent stand was considered to be at capacity, whereas there were no spectators present north of the considered area. The seats in these stands are typically sold to encourage spectators who support the opposing team o sit together. The authors acknowledge that this study is limited to footage obtained from publicly supplied video, and therefore there is a gap in the pre-evacuation behavioural observations of all spectators. The reported quantifications herein are noted as estimations because the smoke and camera quality impair the visibility. The videos were time-matched by the authors based on key events to create a global timeline of the fire and observed behaviours (see Section 4.2).

3.3. Study Limitations

There are inherent limitations in this study due to the low number of locations studied and the low number of scenarios observed. While circulation (i.e. regular post-game egress) is extremely common and collecting footage is therefore easier, higher-motivation egresses such as the rain scenario and fire scenario herein are considerably rarer and therefore much harder to capture. It is rare to get multiple instances of genuine rain or fire evacuations at the same venue, let alone capture that data for analysis. Thus, the available dataset is limited to the three scenarios described herein, with one trial for each scenario. As such, the conclusions of this study are limited to the specific scenarios discussed. Each scenario has a different distinct cause and conditions for egress, leading to different results. These results do not imply that an egress under these conditions (Normal, Rainfall, Fire) will always have the same effects, as behaviour may be influenced by additional unspecified factors such as architecture, demographics, venue, etc. Counter-flow was observed, particularly under normal conditions, which could also impact the flow of patrons in an inconsistent manner. The fire scenario observed has a particularly low occupancy, and footage was captured by several bystanders and TV broadcasters, instead of from researcher-controlled cameras. The behaviours observed were compared however with other similar stadium fires, as seen in sections 4.2.2 and 4.2.3, to expand on the available data. This study is first stage and designed to be built upon with additional data and analysis considering more of these rare events and their distinct conditions.

4. Behavioural Observations

4.1. Standard Post-Game and High-Motivation (Rainfall) Egress Studies

The standard post-game egress at the Tennis Stadium was analyzed in over 13 minutes of video footage. It is important to note that the video was recorded at the end of the second to last match so egress would be influenced by crossflow from other entering spectators. Table 4 lists the timeline and observed behaviours that influenced egress. The origin (00:00 time) is when the match had ended. The overall egress of the stadium from this match was approximately 13 minutes with no observed signs of excess congestion or competitive behaviour.

Table 4. Decisional Behaviours of the Standard (Post-Game) Egress

Time in videos (m:ss)	**Decisional Behaviours and Key Events Observed**
0:00-0:30	• Even though the match has ended and employees have opened aisle barriers, there are still spectators watching the court players. Main egress begins where spectators predominately exit the gate they entered. • At approximately 15 seconds 8% of the population is in movement, by 30 seconds this is 14%.
0:30-0:48	• Spectators begin egressing but some stop mid stairs to look at the court activities (1.5% of total population). These spectators loiter at the perimeter of the bowl again watching the court activities. Stairs begin to show congestion with starting and stopping of spectators.
0:48-0:58	• As this match has ended, a new match will begin in about half an hour, evidence of cross flow occurring with people entering.
0:58-1:48	• Players exit the court and applause stops, egress increases
1:48-3:48	• An interview begins of winning player shown on stadium screen, similarly before egressing people stop and watch the screen periodically. Some have not left their seats.

3:48-4:35	• Once interview ends, egresses pick up. This is the last game related activity. Peak flow occurs at 89 Ped/min/m width.
4:35-7:06	• After peak flow, egress subsides. Announcer comes back on to announce winner and waive of prizes. This again results in a distraction of people leaving the stadium (loiter in the bowl and on the stairs), where 1.8% of the total population per stand some turn back. • Only 7% of those in attendance remain sitting and not in the process of moving by 4:35.
7:06-8:24	• Final acknowledgements by announcer.
8:24-13:05	• Gate usage is steadily decreasing from 20 Ped/min/m to minimal.

For the rain evacuation at the Tennis Stadium, the total recorded egress was 2 minutes 55 seconds. Table 5 displays the timeline and observed behaviours which appeared to influence egress. The origin (00:00 time) is taken as just a few seconds before a formal announcement is made, because at this time, some spectators had already begun evacuating. It is here that some of the same behaviours observed in the fire event (next section) are revealed. Normalcy was quickly subverted, as the game was immediately stopped, a clear deviation from normal gameplay. Potential Authority actions and influences were observed, with the entirety of the stadium standing to egress within seconds after the Chair Umpire, who prominently holds the highest form of authority for players during the match [24] and is heard by all audience members, announced suspension of play. The authority exhibited here may be similar to the Beverly Hills Supper Club Fire, where a busboy interrupted a performance to advise spectators of a fire and is a frequently documented factor in egress while people are being entertained [25].

Table 5. Decisional Behaviours of High-Motivation (Rainfall) Egress

Time in videos (m:ss)	**Decisional Behaviours Observed**
0:00 -0:08	• Rain approaches. Employees open gates at 0:00, where game is suspended by announcer at 0:03, rain encompasses stadium by 0:08. Evacuation is largely simultaneous at suspension announcement. • There are few (<10) who while seated pull out umbrellas, about 20 who do not have umbrellas stay seated. • Majority go to closest gate relative to seating.

0:08-0:19	• As congestion at some gates begins (climbing rapidly to 120 ped/min/m), there are 4.5% of the pedestrians that do not use the closest exit and switch gate destinations on their journeys. At this point, queuing develops at all gates. Queues range in length to about 5-10m. Queues are directed against the wall as there is some shelter there. • People are carrying possessions including food. • Elderly people seen clearing a path in queues with walking stick, hitting others out of the way. • At approximately 15 seconds 97.5% of the population is in movement.
0:19-0:20	• Rain intensifies. Spectators who remained seated without umbrellas begin to evacuate.
0:20-2:45	• At 0:20, peak congestion is seen which steadily decreases until the stadium bowl is empty at 2:45. Those with umbrellas remain committed to their seats.

Figures 5 and 6 describe the percent population egressed with time and the flow of persons per minute per exit width with time for the standard and high-motivation egresses, respectively. The timelines can also be referenced with Tables 4 and 5 above, for detailed time markers and event descriptors which correlate to the observed max peaks seen based on specific events seen in the stadium egress. Figure 3 is helpful for reference as it illustrates an observed gate.

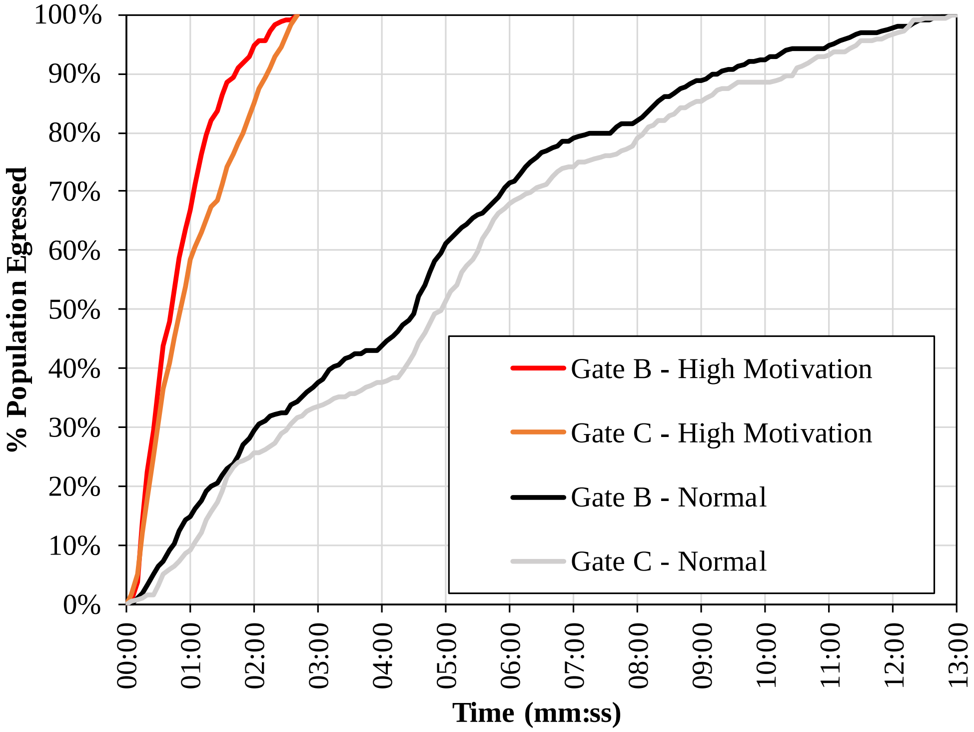

Figure 5. Percentage of population egressed for Normal and High Motivation Stimuli

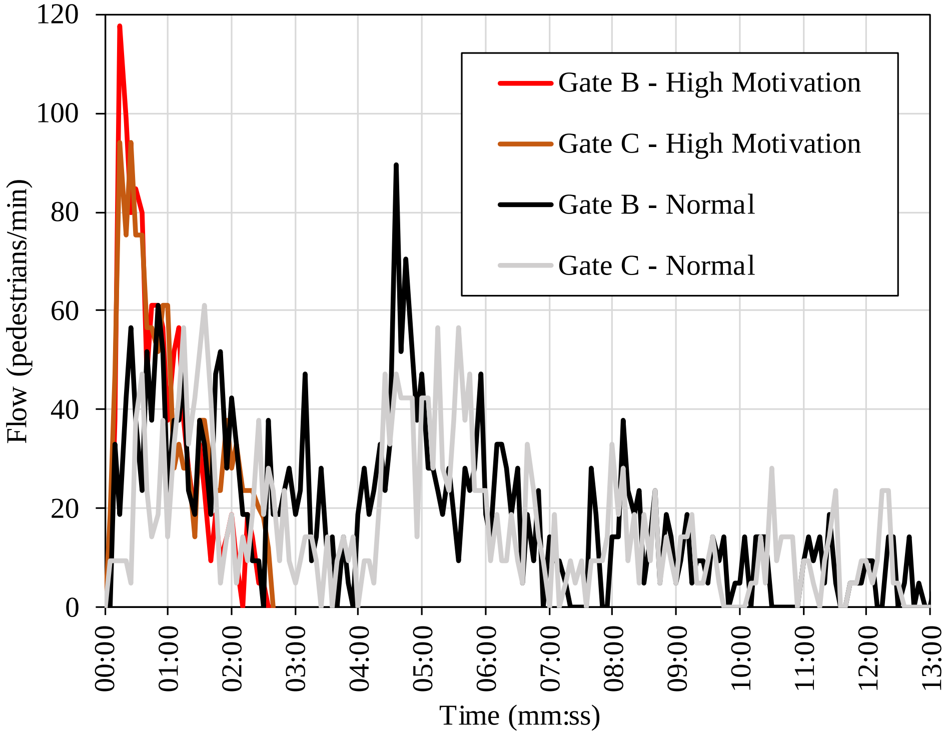

Figure 6. Flow at Gate for Normal and High Motivation Stimuli

The normal post-game egress was very long and distributed (spread out). The first major wave of spectator egress starts at time 0:00 with the completion of the game. Egress slows at around 1:40 as an interview with the winner begins. During the interview, egress slows down. The interview ends at 3:48, cueing applause, followed by the next big wave of spectator egress at 3:57 to 6:50. During this time, the greatest flow is recorded as 89 ped/min/width. From 6:50 to the end, the remaining 20% slowly dissipate. These time markers can be referenced in Table 4 above.

By direct comparison, the egress behaviour observed for the high motivation rain evacuation displayed a very different trend; the evacuation was faster and steadier. The pre-movement time was overall short (about 10 seconds), with some spectators (about 5%) beginning their egress before the game suspension announcement. The rain quickly intensified, potentially subverting the optimism for spectators that the rain would be minor and leading to a greater incentive for people to seek shelter inside. The persistence of the rain may have acted as a constant evacuation cue to which the spectators were exposed. The greater flow observed is what led to queuing and congestion that was unseen in the regular egress (see next section). It is important to remark that peak densities (120 ped/min/m High motivation and 90 ped/min/m Normal) seemed to be correlated to the announcer calling the cessation of activities of the match regardless of the stimuli. However, the densities were higher with the stimuli despite the lower number of spectators in the stadium.

4.1.1. Queuing and Congestion

The observed behaviours described above lead to specific trends in the overall egress of these stadia which are supported with the following quantifiable data. Figures 6 and 7 illustrate the accumulation of people arriving at and departing from the exit corridors from the left, right and center aisles of the standard and high-motivation egresses, respectively. For comparison, they are scaled to the same x and y axes. A visualization of a gate is provided in Figure 3.

The standard egress event exhibited a higher volume of people. This, together with the dispersed egress patterns due to post-game announcements and the relatively slow movement due to low motivation, caused moments of temporary congestion throughout all walkways. However, there were no accounts of quantifiable queuing (Figure 7). Pedestrian movement was often impeded because of the overall higher number of people and other spectators choosing to relocate and loiter (a behaviour not seen in the rain evacuation). Although this caused moments of congestion due to a reduction in passageway width, flow was overall maintained which led to no accounts of queuing. Figure 7 illustrates this, in which there are no deviations between the arrival and departure lines, meaning that no person was ever waiting in a lineup to exit through these gates.

Conversely, the rain event exhibited congestion and queuing formations, particularly around the gates despite the significantly lesser population. This was because of the fast, immediate and simultaneous evacuation. Queue development is illustrated in Figure 8 when the amount of people arriving at the gate surpasses the amount of people that have exited the gate. This queue can be quantified by the difference in these two values (arrival at the gate and departure through the gate).

The flow rates for pedestrians is different based on the direction of approach and location relative to where the audience was sitting. Figure 7 illustrates the difference in flow rates for each direction through Gates B and C. For both gates, the flow from the center is low compared to the left and right entrance flows. This is because spectators entering from the center were limited to using the stairs directly in front of the gate. As seen in Figure 3, these stairs do not serve all rows, and only provide access to a smaller triangular section of seats on either side, compared to the other seating sections. The left and right flows accommodate multiple sets of stairs serving larger sections, and thus a greater number of pedestrians were observed using these.

This effect carries over into the high-motivation egress event. The lower demand of the center stairs led to overall lower flows approaching both gates from the center. Furthermore, little to no congestion or queuing was observed on this approach, compared to the higher congestion observed on the side approaches.

The flow rates for each gate's side differs, with the left approach for Gate B being more popular than the right approach, and the right approach being more popular for Gate C. This also carries through in the high-motivation egress. This is likely due to the seating locations of the spectators. The stadium is highly symmetric, but the rows extend down further on either side of the court as seen in Figure 3. These additional rows increase the number of spectators in these sections, and thus increases traffic when the spectators egress. As seen in Figures 8 and 9, Gates B and C are located on either side of this larger section, and the increased popularity of each gate's side corresponds to the location of the larger section.

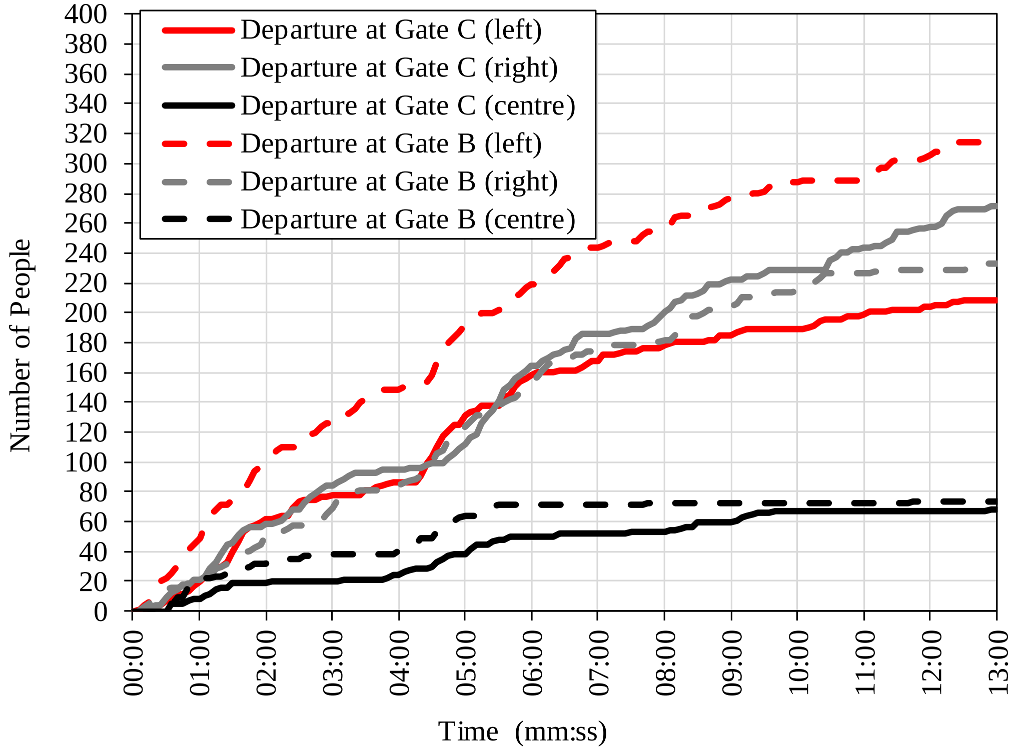

Figure 7. Cumulative arrival and departure for the standard egress at Gate B and C

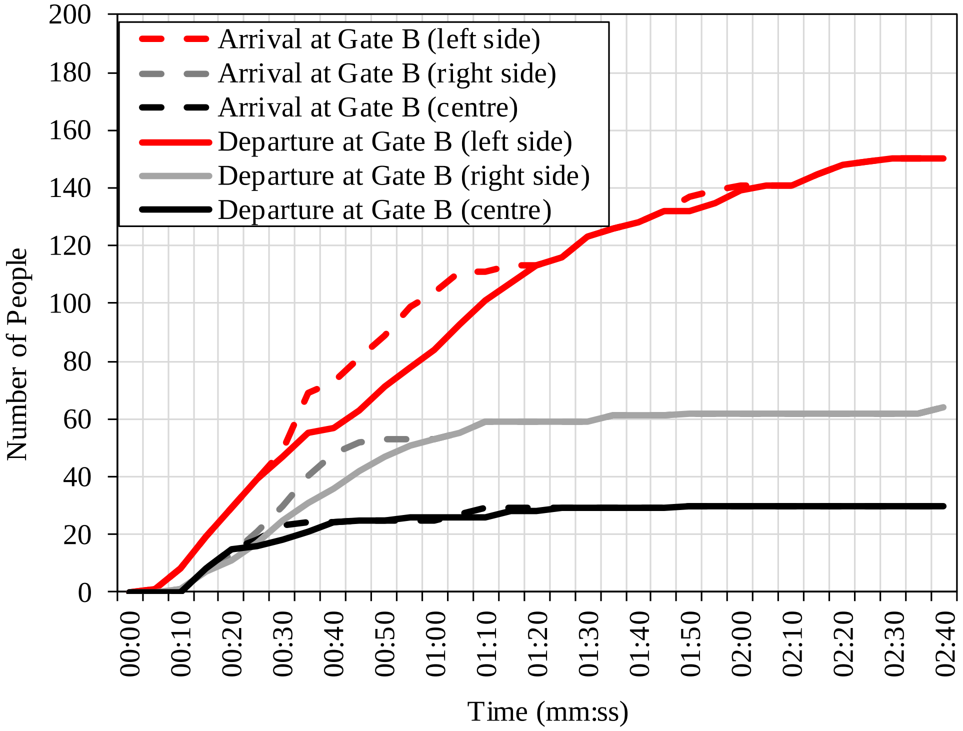

Figure 8a. Cumulative arrival and departure for the high-motivation egress at Gate B

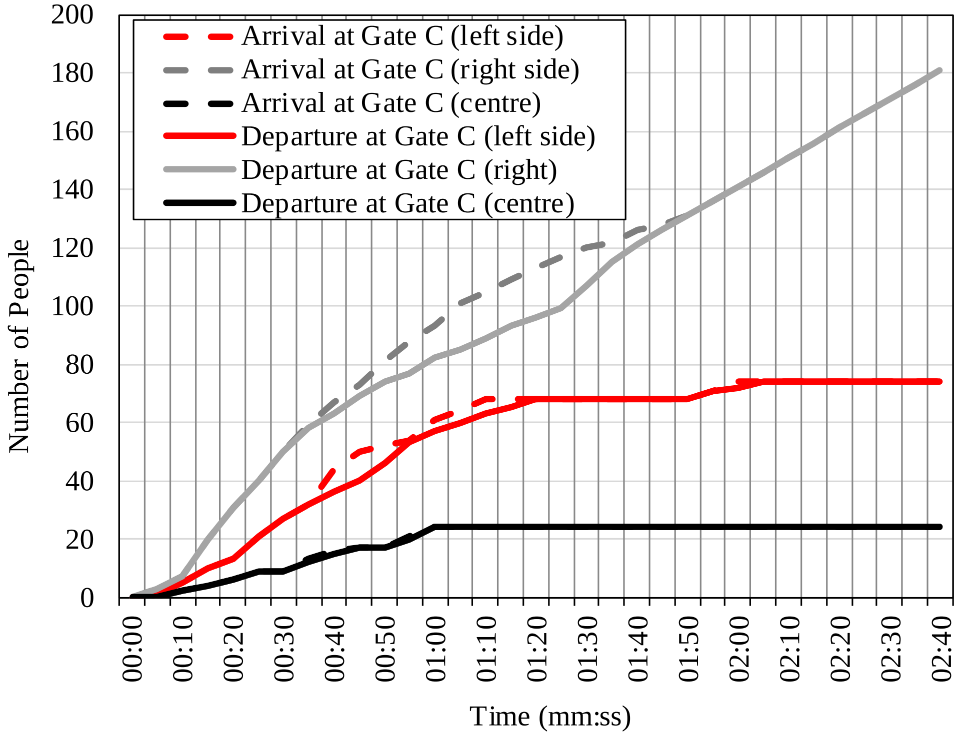

Figure 8b. Cumulative arrival and departure for the high-motivation egress at Gate C

4.1.2. Wayfinding

Figures 9 and 10 describe exit use distribution during egress. They were developed through tracking occupants from their seat location to the exit they chose in each of the videos. With this, these figures illustrate the percentage of spectators in each respective section who chose to egress at their assigned gate (denoted by straight arrows), and the deviating percentage of spectators in that section that chose a further egress path to the next closest gate (denoted by curved arrows).

The regular and rain egress showed similar behaviour in wayfinding, whereas the rain evacuation showed more defined and systematic trends. The regular evacuation showed more deviation in the way people chose to exit. In both cases, most people used the closest exit for their egress.

Those who did not pick the closest exit instead chose the next closest exit, which was found to be the corridor that they first entered. Hence, primary choice of wayfinding is to the nearest exit or whichever is most familiar to them that the entered from. With this, it was found that the crowds migrated towards the direction of the main entrances (Gate A, B and C, where the only 2 elevators are located in the back concourse). These findings are attributable to behaviours outlined in Tables 4 and 5. These behaviours may serve as examples of familiarity to choose the exit that is most familiar.

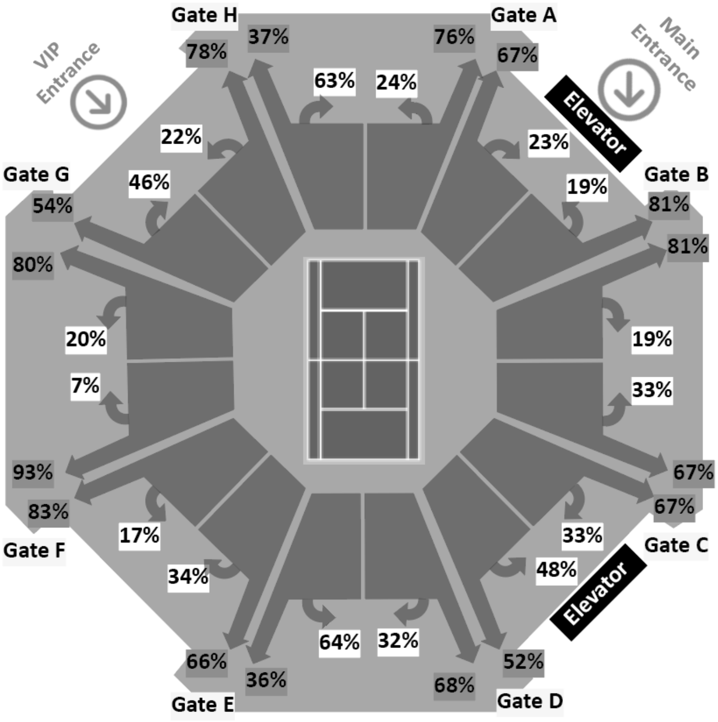

Figure 9. Exit use distribution for the standard egress.

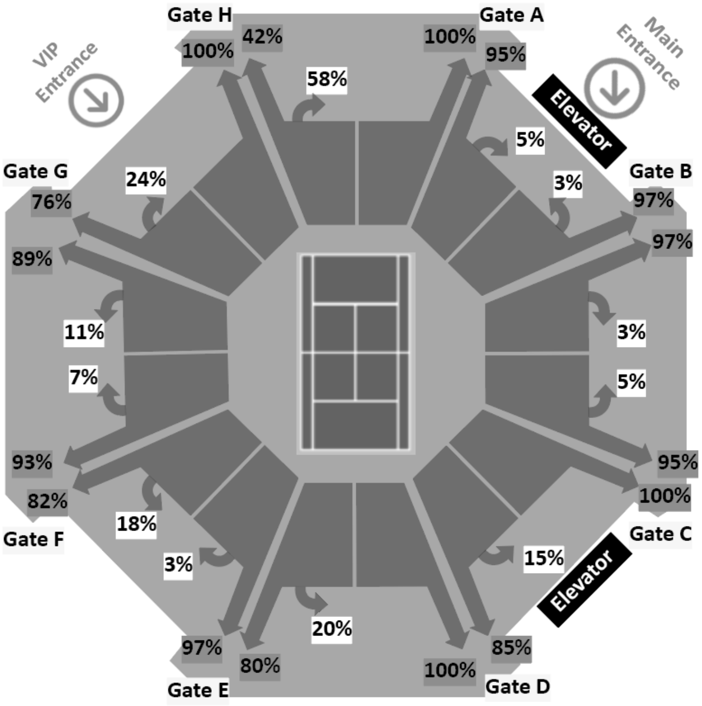

Figure 10. Exit use distribution for the high-motivation egress

4.2. Emergency (Fire) Egress Study

As ethical considerations prohibited an emergency evacuation of the tennis stadium, the authors supplement motivational comparison with the observations from a Canadian football stadium they had access too. That stadium had a small isolated fire (the fire did not spread beyond its point origin in the stands). So as to be conscious of its representation and reinforce behavioural findings, this event is then compared to the analysis of a North American football stadium fire and historically to a European Football (soccer) stadium to verify behavioural and management description findings. As footage is not strategically filmed to quantify all aspects of density, only a qualitative in nature timeline is available for these case studies as a quantitative analysis is not possible.

4.2.1. Canadian Football Stadium Fire

The total recorded egress was analyzed over 2 minutes 55 seconds for the fire evacuation at this stadium. A timeline is presented in Table 6 with visual references to Figure 11. This was attributable to the time it took for approximately 120 spectators to evacuate the local stands from the time that smoke was visible. The origin (00:00 time) is taken as the earliest available footage the authors obtained, when the fire had already been lit and dark smoke was emanating from the stands. Despite visible smoke and flames, non-involved fans did not begin to egress until the small explosion was observed, over 35 seconds after the start of the video footage, and more than 30 seconds after fire was visible. The smoke appears as though it did not act as a cue to evacuate, as it was only when an explosion was observed that pedestrians were seen to move. This may be an example of normalcy behaviour, as the spectators could have thought that the situation was somewhat low-risk and normal. In sports culture, particularly in Europe, the lighting of flares by fans is not uncommon for certain clubs [26]. Even after the explosion, most spectators only shifted over a few seats, and it took a few seconds for another group of spectators to start their egress. 16% of spectators were observed filming the incident on their phones, sometimes blocking egress routes or even getting closer to the incident. This may also be an example of optimism, as those who chose to film likely assumed that they could do so somewhat safely, and that there was no danger present in doing so. This could also be attributed to bandwagon behaviour, as one person filming influences another and so on. Additionally, this could be an example of attentional behaviour as spectators are focused on the event as it unfolds, missing potential cues as the situation evolves. An illusion of control can be observed after the banner catches fire, as some members attempt actions to keep their fire under control, despite lacking a fire extinguisher. Bandwagon and authority behaviours were also seen as most masked individuals stayed together in the stands, with some following one flag-bearer when he made his way to the exit. The authors though suggest that the behaviour being seen is more akin to a social identity being developed among the fire setters (see reference [27]). The behaviours seen in this study can be supported by very similar behaviours presented at two notable case studies – the recent 2019 fire at Nissan Stadium, and the historic fire at Bradford City Stadium in 1985 – discussed further in the following subsections.

Table 6. Decisional Behaviours of Emergency Egress for Canadian Football Stadium

Time in videos (m:ss)	**Decisional Behaviours Observed**
0:00 -0:15	• Dark smoke begins to emanate (0:00). Spectators are not evacuating at this point. By 0:06, fire is now visible. By 0:15, a flare is thrown on the field.
0:15-0:28	• Staff arrives to remove the flare from the field and spectators are seen dancing (now masked).
0:28-0:35	• An explosion is heard, and most spectators are now evacuating. Some remain close to the fire and begin to film. Some not filming are fixated watching the fire without filming.
0:36-0:50	• Additional people begin recording the fire, egress in the northern portion for the stands (direction of smoke plume) is well underway. • Spectators are seen carrying bags and possessions in egress.
0:51-1:02	• Some spectators evacuating to the east are blocked by masked spectators with a large flag which at 1:02 catches fire.
1:02-1:08	• Spectators attempt to remove fire source underneath large flag. Staff begin fighting fire with extinguisher. Masked spectators begin tearing up flag but fire spreads. Spectators continue to film.
1:08-1:22	• Security staff suppresses fire.
1:22-1:52	• Spectators continue dancing in stands (see Figure 11a). Staff members begin directing those remaining sitting to egress.
1:52-2:07	• Second explosion is seen when staff member lifts trash can lid. Remaining masked participants begin to exit on direction of staff and follow flag bearer (see Figure 11b).
2:07-2:55	• Last remaining people in stands are cleared out.

Figure 11a. Masked participants remaining in stands despite banner on fire

Figure 11b. Masked participants remaining in stands following flag-bearer to egress

4.2.2. Pyrotechnic Machine Fire at Nissan Stadium

On Sunday September 15, 2019, a pyrotechnics machine caught fire on the field of a National Football League Match in Tennessee's Nissan Stadium. Similar to the analyses performed on the Canadian football stadium fire, the authors' access to credible and comprehensive footage of the case study is limited to publicly shared recordings and photos (these do not have clearances though for publication but are readily found upon reasonable online searches at the time of writing).

Similarly, it is noted that the initial stages of the fire and the associated human behaviours cannot be considered since the available footage only commences when the fire has already reached a substantial size. It is also noted that this fire propagated more rapidly than usual as a result of the highly combustible and readily available fuels of the machine. The event fortunately caused no casualties or reported injuries. In both events, the game was not stopped.

In turn, this case study reveals similar occurrences of pre-movement and egress behaviours outlined as seen in the Canadian football stadium. Table 7 describes the observed behaviours in a timeline of key events. The origin (00:00 time) is noted to be the earliest available footage, at which time the machine has been entirely engulfed in flames, and the resulting smoke is directly affecting the nearby stands.

Table 7. Decisional Behaviours of Emergency Egress for American Football Stadium

Time in videos (m:ss)	**Decisional Behaviours Observed**
0:00 -0:04	• Fire engulfs the machine with thick black smoke. Security is on scene quickly but is not directing evacuation. Players and spectators are not evacuating and begin watching the fire.
0:04-0:19	• Staff begins moving combustible objects away from the machine, photographer approaches the fire for a photo. At 0:06, a staff member attempts to put out the fire with an extinguisher. At 0:07, a second photographer approaches. At 0:19, the fire extinguisher runs out of substance and the staff member then begins to order spectator to evacuate.
0:20-0:26	• Evacuation begins, but many spectators do not follow directions. This tends to be in localized groups in the stands. Spectators can be seen filming with their cell phones.
0:27-0:40	• Fire decreases in size by about 3 x the surface area. Staff attempts to fight fire further, but extinguisher is out. By this time, the first five rows are evacuated. Some begin trying to come back to their seats.
0:40-0:50	• Visible fire is put out by staff.
0:50-1:08	• Smoldering fire is put out and spectators allowed to return.

4.2.3. Bradford City Stadium Fire

On Saturday May 11, 1985, a lit cigarette ignited the wooden stands of the Bradford City Stadium, causing a rapidly growing fire during an English League match. The fire and resulting smoke engulfed the entire stand in less than four minutes, resulting in 56 casualties and an additional 265 non-fatal injuries. The Bradford City Stadium fire was well documented as recorded by Yorkshire Television followed by investigation from the Popplewell inquiry [28]. The fire severity of this particular incident is much greater than that seen in the other stadium fire case studies but does share similarities from a management and behaviour perspective. Table 8 identifies behaviours observed in reference to recorded footage. The origin (00:00 time) is noted as 3:44PM, when the fire grew to the stands. At this point, the fire was significantly noticeable.

Table 8. Decisional Behaviours of Emergency Egress for Bradford Football (Soccer) Stadium

Time in video (m:ss)	**Decisional Behaviours Observed**
Prefilm [26]	• Archived photography illustrates the beginning of the fire. It illustrates smoke emanating between laminate boards in the stands. Local egress has occurred, but several fans are watching the smoke and development about 1m away. Photos are being taken.
0:00-0:12	• Fire is seen in the film and is identified by the TV commentator. It can be seen people are moving away from the fire, but they stop short of the entry to the field. Police are prompting people and directing them away from the fire and then on the field. Away from the fire in the stands, nearby people continue to watch the match as it is still in play.
0:12-0:24	• People in stands away from the fire move closer to the smoke to appear to investigate. Smoke is getting thicker.
0:24	• Game is stopped. People now enter the field.
0:24-0:47	• Spectators are jumping the wall to the field. People are observed being trampled in this process if they fall. The fire now has engulfed about 6 rows. People elsewhere are cheering for the game as they are being evacuated. Spectators are also watching the fire develop.
0:47-1:22	• Smoke is dense and takes over the whole stand. Spectators are observed helping each other over the wall and onto the field.

1:22-1:40	• Roof is now on fire. At this stage, people are still attempting to get onto the field but heat from the fire is now affecting the spectators and harming them.
1:40-2:27	• Field area in immediate area of the fire is now been cleared of people. At the mid-section, it is still clearing.
2:27-3:00	• Crowd on field is mostly staying in the location they are, people are still leaving the furthermost sections. By 3:00, an elderly person is observed being dragged out of the stands.
3:00-3:25	• Stands completely engulfed.
3:25-4:15	• There are people still evacuating stands, though footage shows people in the fire. Police officers are filmed directing spectators to assist in evacuation. 15 people help put out a fire on a man.
4:15-4:49	• First responders arrive on scene and footage concludes.

4.3. Observed Similarities and Differences between Studies

Similarities can be drawn between the three egress stimuli studies. All three took place in a Canadian sporting stadium and resulted in an effectively complete egress of spectators. Of the two non-standard egress events, both occurred under high-motivation stimuli (rain and fire). All scenarios included some degree of influence of authority to prompt or influence evacuation, whether from announcers or stadium staff themselves. However, significant differences were also observed with regards to total egress times, pre-movement, behaviour, and observed congestion.

Despite the significantly larger population and size of the rain event, total egress times were less than the observed time for all of the emergency fire events considered. The authors believe that this is heavily influenced by the perception of threat communicated by the authority figure – for example, in all fire case studies, the size of the fire correlated to the urgency of the staff to evacuate spectators. The stimuli of the rain also affects all people in the stadium which may have caused increased congestion of all egress routes whereas the fire event was a highly localized event so levels of high motivation were differently spread between the two events. Higher pre-movement times in fire scenarios contributed to the longer egress times, though where staff was unsuccessful in having members within the stand leave which possibly leads to the role of social identities and group formations within the stands (i.e., those filming or those causing vandalism for small examples).

In the Canadian Football Stadium Fire event, for example, some members of the population were actively participating in the events leading up to the fire. This resulted in a longer egress time for these members as they had to be directed, both by staff members and the leader of their group, to evacuate the stands. This took some time, as a fire in the stands was not expected nor necessarily planned. In contrast to this, the suspension of play due to rain in a tennis game is an expected occurrence as rain was forecasted, therefore the event was potentially expected by both spectators and staff. Staff response in this case was also much quicker, with play suspended only a few seconds after the initial start of rainfall, and some spectators standing to leave even before the suspension of play was announced. The egress during the rain event was implied through standard procedure and an announcement by the Chair Umpire. The Chair Umpire's announcement to suspend play has an effect of directing the audience how to act. In the case of the rain event, this appears to have induced the evacuation process for most of the audience. In the case of the normal egress, it delayed it and contributed to congestion and cross flow. Similarly, during the Bradford fire, police officers directed evacuees to enter the pitch, influencing the route evacuees took – but this was only followed upon when the game was stopped. These are examples of Authority bias. Conversely, the lack of instructions from a figure of authority can have a delaying effect, as observed in the standard egress which came with no explicit instructions on when to leave, or the Nissan and Canadian football stadium fires where authority figures did not direct egress until after attempting to put out the fire. For example, the reaction of authority was much faster than that observed with the Canadian football which is likely due to the size of fire observed and associated threat.

The major behaviours of the emergency event, namely attentional, optimism, and bandwagon behaviours were observed in all scenarios. However, these behaviours were not as widespread, and the effects manifest in slightly different ways. Similar to the fire event, attention played a role for some spectators who continued to watch the tennis game even as the rain started to fall. However, this was quickly subverted by the announcement of suspension of play. With the item holding the attention removed by an authority figure, the decision for many could have switched from stay to evacuate. However, this does not mean all spectators evacuated. Optimism behaviour also likely played a role for some audience members who chose to stay in their seats with umbrellas and try to wait out the rain. However, as the majority of the audience chose to evacuate, bandwagon behaviour may have encouraged many of those who initially tried to wait out the rain to evacuate as well.

In the standard post-game egress, potential attentional and bandwagon behaviours were also observed, as multiple rounds of applause and events caused leaving spectators to pause and, in some cases, return to observe post-game activities in the stadium. This had a positive effect on egress in this scenario, as it reduced the flow of people through the exits and preventing queuing from occurring.

Pre movement behaviors also substantially differed between the events, for example at 15 seconds 97.5% of the population was in movement towards an exit in the rain event compared to 8% of the population in the regular end game egress. It would not be until over 4 minutes for an equivalent majority of the population to be in movement in the regular end game egress.

During the actual egress of the rain event, several spectators were observed running to the exit. This is a high contrast to the Canadian Football Stadium and Nissan Stadium fire events, where spectators were only observed walking to the exits. In the Bradford Fire, running was also observed as spectators egressed onto the field. This may have been due to the persistent and unpleasant egress cue delivered by the falling rain in the rain event, and the heat from the large fire in the Bradford event. Planning fallacies may have played a role in both of these events, as in both cases the hazard arrived quickly, leaving very little time for the spectators to evacuate once they started to experience the hazard.

It is important to also note the cultural and demographic differences present in each event, as the audience of a football match likely has a different demographic distribution compared to a tennis match. The audience members involved in the fire events appeared to be young adults and adults, whereas both events at the tennis stadium consisted of a much more diverse population, with families and seniors also observed in larger numbers. In terms of movement, observations from the fire event show that their pre-movement times can be longer than expected, especially if an individual is a member of a group closely involved in the situation. Cultural implications can have an additional effect through anchoring behaviour. During standard post-game egresses, cultural expectations of post-game events can distribute the pedestrian demand over a longer period of time to prevent crowding. Conversely, this can have negative effects in emergencies, with the football culture of not going onto the pitch causing some delay in getting evacuees to evacuate onto the pitch during the Bradford fire.

5. Future Research

5.1. Recommendations for Future Studies

The examination of multiple egress types has highlighted the importance of considering the hazard and environmental factors in emergency egresses as they may influence the behaviour of evacuees. The variation between different hazards and stimuli may potentially alter premovement times, decision-making, and flow rates. However, these hypotheses cannot be confirmed given the limited number of scenarios, trials, and observations herein. Thus, there are several potential avenues for future needed research to further validate, refine, and expand upon this work.

Additional scenarios and trials are needed to generate more observations to validate the observations made here. In order to do this, a methodology to standardize experiences is needed, allowing the comparison of similar or identical scenarios to make robust conclusions. This is a considerable challenge as fire scenarios in stadia are rare, and do not occur in a controlled environment where all variables can be kept constant. Rain events and other adverse weather events that would cause a high-motivation egress are more common, but architectural, population, and demographic differences may still exist. It may be useful to create a method for archiving footage of abnormal egresses in stadia, even if using third-party sources such as cellphone videos and security footage to collect the data.

Other scenarios not studied in this paper but may still be of interest include terrorism and presence of explosive devices, as these scenarios are extremely rare but also are likely to result in different behaviours. The role of authority figures and staff should also be examined in more detail to see how their actions affect stadium attendees during emergency egresses, and what role information from announcements, signage, or trained staff has to play. This would not only be useful for confirmation and validation for modelling, but also for the development of more effective evacuation methods, techniques, and technology.

Different cultures across the world may also lead to variations in how stadium attendees behave and move. These cultural differences should be looked at in detail and may warrant its own independent research to determine how applicable data from abroad can be applied to similar scenarios involving a more local population, not just in evacuation of stadia, but evacuation and circulation in general. These are just some examples of potential additional research that can be done to help reveal and confirm the factors affecting pedestrian egress.

5.2. Recommendations for Future Evacuation Modelling

Human behaviour is important to consider when constructing computer models of stadia for egress. The congestion and high traffic volumes observed during the rain evacuation further highlights the need to model evacuations and egresses to ensure suitable designs. It also exemplifies the need for modelers and practitioners to understand the role of the authority figures such as staff and announcers in the stadia.

Practitioners' models should account for a specific range of scenarios that will influence human behaviour in egress. In some cases, environmental conditions for open aired stadia need to be understood in association to egress. It is noted that these behaviours and staff roles noted herein were determined using limited data from only a few events, limiting the results to similar scenarios and stadia.

Inputs regarding pre-movement delay is one of the main egress parameters and is affected herein by the authority figures. For example, when modelling a fire egress, the pre-movement times may be impacted by spectators who delay their evacuation to take photos or continue to watch the game if it is still ongoing. This lack of movement can be observed especially if the fire is in the early stages or is further from the spectators. Standard post-game egresses can also be very spread out and in excess of minute rules in guidance and standards, especially if post-game events and activities are held – though these will occupy the spectators during egress, minimizing anxieties, but may also introduce distractions and cause injuries just the same as crowding, and congestion on stairs, walkways and exits can still occur. In high motivation exits where play is stopped and an external stimulus supplied (rain in this case), pre-movement times may be negligible and a simultaneous evacuation may take place.

Route choices are also affected by behaviour, as observed through exit selection. In both the standard and rain egresses, most spectators tended to use the closest exit (rather the exit they came in). In the recorded rain event, it was also seen that spectators tended to maintain a chosen route towards their target exit, which rarely changed even as other exits or pathways became less congested.

Social identity influences the decision to evacuate; evacuation is delayed if others are similarly not evacuating or the group is participating in part of an activity. Conversely, the choice to evacuate sooner could be made if others nearby also start evacuating. This also applies to standard post-game egress, with some audience members staying around and others choosing to leave.

While it is beyond the scope of this paper to represent movement speed and anthropometry data, this will be needed in the light of dated movement speeds that do not represent the demographics seen in stadiums today or may not be tailored for stadiums. That topic area is currently under development by the authors elsewhere [15].

6. Conclusions

This study examined the egress of stadium patrons under several different motivational conditions, using footage collected at Canadian stadia. The footage was analyzed by multiple researchers to determine flow rates and actions taken by stadium patrons under the different conditions (Normal, Rainfall, Fire). By comparing the results of the three different egress motivational conditions and their stimuli, several key findings were revealed and determined:

- The egress of stadium stands differs depending on the nature of the motivational scenario but evacuation is influenced by actions and directions of authority figures;
- Movement through the stadia is heavily influenced by normality, attentional, optimism, and bandwagon behaviours;
- During a standard post-game egress, spectators are more likely to take longer to initiate their egress if post-game activities are still occurring on the field. This can cause congestion on passageways as they stop to congregate;
- Despite egresses taking longer in normal conditions than would be specified in guidance, there was no evidence of visible anxiety in the spectators in this process;
- During high motivation scenarios, faster evacuation and higher traffic volumes were observed with greater congestion at exits being observed compared to normal evacuation;

- The differences between the high-motivation rain event and the fire events were potentially influenced by the state of play on the field, as play was not stopped during the fire event. Furthermore, there was an absence of a dominant authority figure ceasing the activities during the fire event; and

- The rain event was found to have lower pre-movement, faster walking speeds, and a shorter evacuation time despite the higher volume of people. Differences here could be attributed to longer pre-movement times in the fire scenarios, which can be further attributed to formed social identities in the crowd (those that investigate, those that leave, and those that participate in vandalism for some examples).

The data presented herein is novel and unique. This large-scale field data has been comprehensively gathered to determine and reveal qualitative behavioural data and quantify egress pattern data. The data has been post-processed to minimize bias in interpretation. The data is indeed helpful now to form initial input assumptions and to design stadia egress and evacuation models. However, this is a first stage study, meant to be built upon where future research should consider utilizing data from multiple egress scenarios to confirm the observations seen. This manuscript's findings are limited to similar scenarios and stadia, as discussed within the limitations of the study, as only one trial of each scenario could be observed. A database of case studies across a diverse set of hazards and egress conditions, behavioural observations, and movement speed profiles would be immensely useful in reducing uncertainty around future predictive egress and evacuation modelling where validation and verification will be needed. This is recommended as a second stage of this research.

Author statement

All persons who have meet authorship criteria in this manuscript are listed as authors. These authors certify that they have participated sufficiently in the work to take public responsibility for this manuscript's content, including the participation in the concept, design, analysis, writing, and revision of this manuscript.

7. Acknowledgments

Organizations thanked for their contributions include the Arup UK Fire Group, Arup North Americas Group, Arup Human Behavior and Evacuation Skills Team, and the NSERC CRD program. The stadium managers and event organizers, who remain anonymous, but granted permission for use of the stadium are thanked for their time and assistance in this study. Technical contributions are acknowledged from Danielle Aucoin and Julia Ferri. Data collection contributions are acknowledged from Katie Chin, Georgette Harun, Chloe Jeanneret, Neir Mazur, and Natalia Espinosa-Merlano.

8. References

[1] Aucoin, D., Young, T., Gales, J. Kinsey M., Mouat, G. (October 2018) The Variability of Behavioural Parameters in Egress Simulations of Stadiums. FEMTC, Washington, DC. 10 pp.

[2] S. Gwynne, L. Hulse and M. Kinsey, "Guidance for the model developer on representing human behaviour in egress models," Fire Technology, vol. 52, no. 1, pp. 775-800, 2016.

[3] B. Poyner, D. Robinson, N. Hughes, M. Young and P. Ayles, "Scicon. Safety in Football Stadia: A Method of Assessment," 1972.

[4] S. G. S. A. (. Britain), Guide to Safety at Sports Grounds, London: Sports Grounds Safety Authority, 2018.

[5] J. Pauls and B. Johnson, "Study of crowd movement facilities and procedures in Olympic Park, Montreal," 1977.

[6] J. Pauls, "The movement of people in buildings and design solutions for means of egress," Fire Technology, vol. 40, no. 1, pp. 27-47, 1984.

[7] National Fire Protection Association, "NFPA 101: Life Safety Code, 2017.

[8] B. Meachan, "Integrating human behaviour and response issues into fire safety management of facilities," Facilities, vol. 17, no. 9/10, pp. 303-312, 1999.

[9] D. Harney, "Pedestrian modelling: Current methods and future directions," Road and Transport Research, vol. 11, no. 4, pp. 38-48, 2002.

[10] M. Haghani and M. Sarvi, "Crowd behaviour and motion: Empirical methods," *Transportation Research Part B: Methodological,* vol. 107, pp. 253-294, 2018.

[11] S.M.V. Gwynne, E.D. Kuligowski, K.E. Boyce, D. Nilsson, A.P. Robbins, R. Lovreglio, J.R. Thomas, A. Roy-Poirier, "Enhancing egress drills: Preparation and assessment of evacuee performance," *Fire and Materials*, vol. 43, no. 6, pp. 613-631, 2017.

[12] J. Fruin, "Pedestrian planning and design," New York: Metropolitan Association of Urban Designers and Environmental Planners.

[13] K. Ando, H. Ota and T. Oki, "Forecasting the flow of people (Japanese)," Railway Research Review (RRR), 1988.

[14] J. Pauls, J. Fruin and J. Zupan, "Minimum stair width for evacuation, overtaking movement and counterflow - technical bases and suggestions for past, present and future," 2007.

[15] J. Gales., et al. “Contemporary Anthropometric Data and Movement Speeds: Forecasting the Next Ten Years of Evacuation Modelling”, SFPE Performance Based Design Conference. 7 pp. New Zealand. 2020.

[16] A. Larsson, E. Ranudd, E. Ronchi, A. Hunt and S. Gwynne, "The impact of crowd composition on egress performance," Fire Safety Journal, 2020.

[17] M. Lindell and R. Perry, Communicating environmental risk in multiethnic communities, Thousand Oaks: Sage Publications, 2004.

[18] Folk, L., Gonzales, K., Gales, J., Kinsey, M, and Carratin, E. (2020) Emergency Egress for the Elderly in Care Home Fire Situations. Fire and Materials (John Wiley). (Accepted).

[19] E. Kuligowski, "Predicting human behaviour during fires," Fire Technology, vol. 49, no. 1, 2013.

[20] E. Kuligowski, S. Gwynne, M. Kinsey and L. Hulse, "Guidance for the model user on representing human behaviour in egress models," Fire Technology, vol. 53, no. 2, pp. 649-672, 2017.

[21] M. Kinateder, E. Kuligowski, P. Reneke and R. Peacock, "Risk perception in fire evacuation behaviour revisited: Definitions, related concepts, and empirical evidence," Fire Science Reviews, Vol. 4, no. 1, 2015.

[22] M. Kinsey, S. Gwynne, E. Kuligowski and M. Kinateder, "Cognitive biases within decision making during fire evacuations," Fire Technology, vol. 55, no. 1, pp. 465-485, 2019.

[23] M. Kinsey, M. Kinateder, S. Gwynne and D. Hopkin, "Burning biases: Mitigating cognitive biases in fire engineering," Fire and Materials, pp. 1-10, 2020.

[24] Tennis Canada, "Rules of the Court 2018," 2018. [Online]. Available: http://www.tenniscanada.com/wp-content/uploads/2018/01/RULES-OF-THE-COURT-2018.pdf. [Accessed 1 September 2019].

[25] M. P. Giesler, Fire and Life Safety Educator: Principles and Practice, Burlington, MA: Jones and Bartlett, 2018.

[26] G. Ruthven, "No pyro, no party: the case for fireworks in Scottish football," The Herald, 22 June 2019. [Online]. Available: https://www.heraldscotland.com/sport/17724213.no-pyro-no-party-the-case-for-fireworks-in-scottish-football/. [Accessed 1 September 2019].

[27] A. Templeton, J. Drury and A. Philippides, "From mindless masses to small groups: Conceptualizing collective behaviour in crowd modeling," Review of general psychology: Journal of Division 1, of the American Psychological Association, vol. 19, no. 3, pp. 215-229, 2015.

[28] Papers of the Popplewell Inquiry into Crowd Safety at Sports Grounds. 1986.