THE USE OF HUMAN BEHAVIOUR TO INFORM EGRESS MODELING IN STADIUMS

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Abstract

With growing concerns of public safety in infrastructure where large crowds gather, designing for egress under normal and emergency conditions is pertinent to ensuring efficient and safe conditions in stadia. There is a need for a large database of publicly available pedestrian movement profiles through experiments and the evaluation of relevant case studies. This thesis outlines novel human behaviour data collection at two stadia. Subsequent egress model validation using the MassMotion Advanced Crowd Simulation Software (MassMotion) was performed and measured total egress times. Although demographics and anthropometry in the stands slightly influenced the egress times, the stadium architecture was the governing factor which impeded pedestrian flow under non-emergency conditions. Analysis of a stadium fire case study allowed for evaluation of this conclusion during an evacuation which revealed that behavioural aspects of both occupant and staff may begin to dominate the egress simulation in an emergency context.

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Statement of Co-Authorship and Scholarly Outputs

This thesis and the work described within have been completed by Danielle Aucoin under the supervision of Dr. John Gales at York University, and in collaboration with Arup. While not identical to the published works, some chapters have been formed into conference papers as follows, with each first draft being written by Danielle Aucoin.

Chapter 3 and Chapter 4: The work described in these two chapters was completed and developed into a conference paper for The Fire Evacuation and Technical Modeling Conference (FEMTC) held in Gaithersburg, Maryland in October 2018. The paper presented at the conference is cited as:

Aucoin, D., Young, T., Gales, J., Kinsey M., and Moaut, G. (2018) The Variability of Behavioural Parameters in Egress Simulations of Stadia. FEMTC, Washington, DC.

Chapter 5: This chapter describes continued work based on research submitted and accepted for a presentation at The 2019 International Conference on Fire Science and Engineering (INTERFLAM). The work that provided the basis for this research is cited as:

Aucoin, D., Young, T., Gales, J., and Kinsey, M. (2019) Modeling human behaviour in emergency stadium fire evacuations. Interflam 2019: 15th International Conference and Exhibition on Fire Science and Engineering. Royal Holloway College, Windsor, UK.

Chapter 1: Introduction

1.1 Stadium Evacuations

Globally, stadia are iconic structures that host events which attract mass crowds. This substantial number of people gathered together in a limited space for extended periods of time raises concern to public safety within these structures. Under the case of an emergency, the stadium may need to be evacuated. These hazards come in various forms such as fire, structural collapse, extreme weather conditions, acts of terrorism, and fights between spectators in the stands. Each of these natural or man-made threats may result in the onset of rapid mass egress. This can result in crowd crushes in which people may be trampled, shoved, severely injured or be a causality to. A crowd crush can be defined as an occurrence when people push into a confined area. When bodies are jammed so close together, the individuals can loose ability to choose where they go and the crowd as a whole can begin to behave like a fluid (Benedictus, 2015). Over the past century, there have been over one-thousand deaths due to crowd crushes in stadia. A table of historic stadium disasters involving causalities can be found in Appendix A1. Through proper capacity and architectural designs and proper stadium operations and safety management, crowd crushes can be prevented. In the case of a necessary evacuation, stadium facility managers and designers need to have a valid evacuation plan to effectively guide the crowd to safety. With the advancement of evacuation modeling techniques developed to consider social forces, it is important for researchers to develop a stronger understanding of a crowd's underlying human psychology.

1.2 Human Behaviour During Egress

It is necessary to study a crowd's social-psychological behaviours to understand evacuations under normal and emergency conditions. In any given egress situation, how a person behaves can be dictated by various person-specific and external factors. Person-specific influences may include an individual's age, gender, bias from past evacuations, whether they have luggage, or whether a person is under the influence of alcohol. External factors may include the weather, walkway terrain, and the behaviours of others around the individual. More insight will be provided in Chapter 2 detailing established and relevant behaviours to this research.

1.2.1 Human Behaviour in the Context of Engineering

The egress design process in structures follows one of two approaches in terms of codes: prescriptive-based design or performance-based design. A prescriptive code includes objective-based detailed requirements based on the specific occupancy type or building use. For example, a prescriptive code would require all occupants to be able to egress from a building in a specific amount of time, without any consideration to optimizing the building architecture and how it may be able to be safely evacuated in durations longer than what the rule prescribes. Prescriptive-based approaches are more commonly accepted in most jurisdictions and have been carried out for around a century (Kuligowski et al., 2017). However, many prescriptive codes lack scientific basis in certain applications since they originated from a specific architectural case but are then developed into rules applied across a variety of structure types.

Performance-based solutions, also referred to as alternative solutions, are being used more frequently to address egress designs for emergency evacuations and for normal egress conditions.

These alternative solutions require quantification of both the Available Safe Egress Time (ASET), defined as the time before conditions become untenable, and the Required Safe Egress Time (RSET), defined as the time for the population to get to a place of safety (Cuesta et al., 2016). As depicted in Figure 1.1, the ASET provided must be larger than the RSET in order for occupants to reach a place of safety before conditions become untenable.

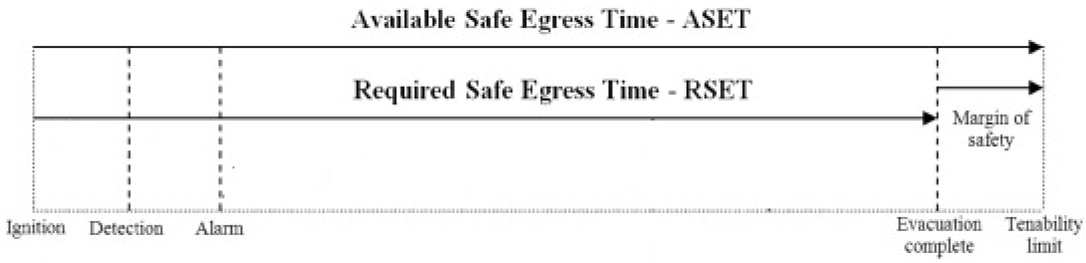

Figure 1.1: ASET vs RSET

This approach has been established by several authorities and code committees to be an acceptable method to demonstrate that a reasonable level of safety has been achieved (Kuligowski et al., 2017). Calculation of the ASET is dependent on selection of a design fire, fire model, and thresholds of acceptable smoke and heat levels. RSET is based on human behavioural factors such as wayfinding and is commonly calculated through the application of an evacuation simulation software in order to process several scenarios and iterations quickly and efficiently. Although simulation software is used for analysis, it is vital for designers, engineers, and architects to understand the underlying needs and behaviours of the structure's occupants. This understanding allows them to provide insight on simulation outputs and ensure design methods more accurately reflect realistic occupant behaviour during normal egress and during an emergency such as fire.

1.2.2 Variability in Human Behaviour

Studies that have been conducted in the human behaviour field are typically based on real evacuation events and experiments, such as the crowd psychology studies carried out by Anne Templeton (Templeton et al., 2015; Templeton et al., 2018). Although research has provided a benchmark to predict behaviour in evacuations, it is important to note that human behaviour assumptions are not based on universally valid concepts such as the laws of gravity. This implies there is an element of uncertainty that comes with modeling human behaviour and predictions must be made on a case by case basis. Behavioural uncertainty can be defined as “the variability of human behaviours” (Ronchi, 2014). An assumption made for one test group of a certain demographic or in one jurisdiction may not be applicable to groups composed of varying demographics or in other jurisdictions. For example, stadium evacuation procedures in the United Kingdom would not typically specify the pitch for egress since the field is considered ‘sacred’ and unlikely to be used without heavy prompting by authoritative staff. Practitioners remain concerned with the reliability of simulations because the calculations performed are virtual. Transferability of models from one application to another must be assessed on a case by cases basis and often requires unique model calibration when applied in various applications. Due to the variability of egress situations in the reality, human behaviour studies should be conducted to validate the simulation modeling used to predict scenarios.

1.3 Stadium Egress Modeling Tools

Computer simulations have become a vital tool for evaluating egress and evacuation processes. This thesis will describe and apply the tool MassMotion Pedestrian Software, which is an appropriate selection for the modeling in this thesis as MassMotion has not been extensively tested in the context of stadia. The software provides industry leading tools to import 3D architecture to be used for applications of evacuations form large and complex structures. The software entails a suite of a wide variety of tools for creating 3D geometry, defining operational scenarios, executing dynamic simulations and conducting analysis of simulation results. MassMotion is a recognized tool for egress analysis as referenced in the SFPE Guide to Human Behaviour in Fire which lists 60 functional human behaviour modeling tools. MassMotion was chosen as the tool of study for this thesis due to its use by practitioners in the local area relative to where this thesis work in being conducted. Local projects involving the use of MassMotion include infrastructure design in Toronto, Canada such as the redesign and optimization of the pedestrian and transit network system at Union Station (ARUP, 2018). This thesis will assess areas of MassMotion modeling that is representative of crowd analyses in stadia. Further detail as to why MassMotion was selected as a Software of choice is provided in Section 2.3.

As aforementioned, validation is an approach that assesses the degree of confidence of the model outputs and how much the results produced will match reality (Ronchi, 2014). However, this definition of validation in the context of simulation models is to some extent up for interpretation. The International Standards Organization defines validation as the "process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method" (International

Organization for Standardization, 2018). Currently, there is no industry-standard set of acceptance criteria for validating a stadium simulation model, which raises concern as to the interpretation of the model results (Ronchi, 2014). MassMotion was not originally designed with the intention for use on stadia but demand from practitioners is growing to prove it as a suitable tool for stadium applications.

1.4 Research Motivation

The Society of Fire Protection Engineers (SFPE) has formulated a Research Roadmap which outlines top priorities of research within the field of fire engineering (SFPE, 2018). As shown in Figure 1.2, human behaviour is ranked as the top priority within this roadmap which outlines the research gaps and needs in the human behaviour category. This thesis aims to address top needs and top priorities identified within the human behaviour section of the SFPE research roadmap framework. Data collection in the field of human behaviour is vital in order to use this data to validate design tools, such as egress modeling software.

Within the roadmap, the bolded topics at the top of each section are the top priorities within each category which include demographic data collection of vulnerable populations. Under the innovative technology section, the roadmap places top importance on the design process involving pre-evacuation times and actions other than evacuating. Under the risk and problematic approaches, the framework identifies large populations as its second most top priority. This thesis will touch upon and investigate experimentally all of these top priorities aforementioned in the context of stadia: data collection of vulnerable populations, investigation into pre-evacuation times and actions other than evacuating at stadia, and risk-based approaches to large populations, since stadia attract highly-attended events.

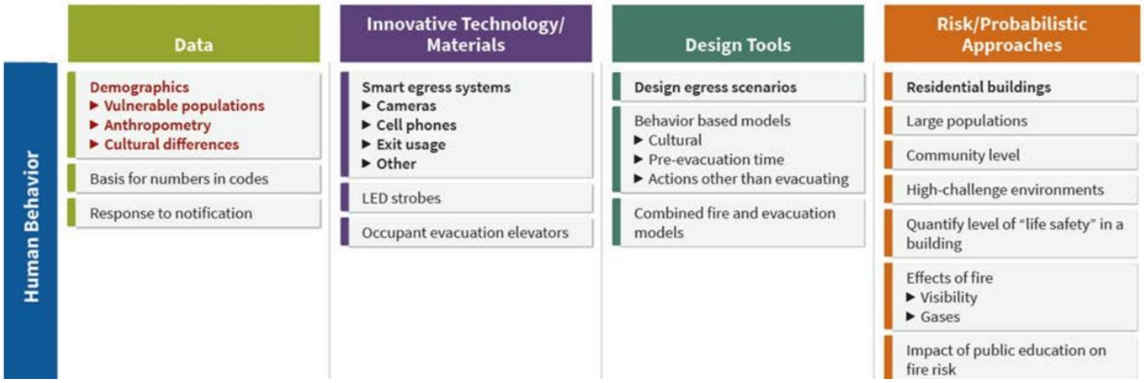

Figure 1.2: SFPE's Research Priorities for Human Behaviour Theme (SFPE, 2018)

With the field of performance-based egress design gradually developing in North America, it is expected to see more alternative solutions in future projects compared to current perspective frameworks. The National Building Code of Canada (NBCC) is objective-based which means that every prescriptive clause is based on functional statements that describe the objectives of that code. NBCC also has a section on "alternative solutions" which allows certain elements to be substituted for others on the basis that it achieves an equivalent level of safety and functionality (MMAH, 2012). This equivalency is done with respect to the objective and functional statements of that approved alternative solution. In Canada, there is a push towards alternative solutions, also coined as performance-based solutions, which are already commonly applied in other countries (Quiquero et al., 2018). Benefits of performance-based alternatives include the prevention of over-design, allowing structures to be optimized in terms of design, materials, and total cost.

In order to apply design tools for novel performance-based design approaches in stadia, it is importance to have a deep understanding of human egress behaviour under normal and emergency conditions. It is evident there is a need for further stadium research for three primary reasons expanded on in this section: the limited number of existing studies, the number of stadium projects are forecasted to grow globally, and recent emergency stadium incidents.

1.4.1 Limited Existing Data and Case Studies

In stadium design, there are various prescriptive 'minute' rules that are used for guidance in planning for pedestrian egress which will be outlined in Chapter 2. Such guidance specifies finite durations in which all spectators should be able to exit from a specific area of the stadium under normal and emergency conditions. However, there is a lack of information as to where these benchmarks originated, what they were initially intended for, and how they should be interpreted in contemporary design. Based on such guidance, engineers may be restricted in being able to fully optimize the overall performance of stadia, as prescriptive rules can result in neglecting consideration of certain aspects of human behaviour. One acceptance criterion for stadium architecture applied in many jurisdictions mandates that all occupants should be able to egress from a stadium in eight minutes (SGSA, 2008). The case behind this eight-minute rule applied to stadia lacks qualitative basis with only a brief explanation regarding a person's stress state in crowds. There is a shortage of publicly available pedestrian studies and corresponding movement data in order to design modern stadia and prove compliance in modeled solutions. It is difficult to study the subject as most data sets remain proprietary in nature, often being performed to only be used internally within a specific project. The resources required to collect and analyze these data sets are also expensive and complex. There are also legal and privacy concerns regarding collecting these data sets and efforts to ensure ethics are obtained and maintained are very important. This resulting scarcity of information for stadia limits practitioners to the few original studies performed in the 1970s such as the crowd movement studies of Jake Pauls at Olympic Park in Montreal and Exhibition Stadium in Toronto (Pauls and Johnson, 1977; Pauls, 1982).

1.4.2 Financial Implications

The incentive to construct arenas and stadia on a larger-scale stems from the associated revenue potential of having more seats to increase ticket sales. For example, The Municipal Property Assessment Corporation (MPAC) has developed a guide on how it places a financial value on large sports stadia in Ontario for taxation purposes (MPAC, 2016). This provincial model aligns with how stadia around the globe are most commonly valued; by the income capitalization approach in which it is assessed on the property's revenue earning power. This requires a detailed analysis of income and expenditures, both for the stadium's valuation being determined and for other comparable venues that have already been operating to use as a benchmark valuation. Aside from space rental leases and concession revenues, the quantity of ticket sales for regular and luxury seats are a significant revenue generator for stadia (MPAC, 2016). Although incorporating a higher number of seats increases initial investment, it does not significantly increase yearly operational expenses which makes building stadia to a larger capacity an attractive investment for municipalities and stadium managers from a long-term perspective. The financial incentive to design stadia to a larger capacity makes egress and evacuation planning extremely important so these highly-populated structures can operate efficiently and safely. A well-planned pedestrian design also makes the building easier to operate from an event management and security perspective.

1.4.3 Human Safety in Stadia

Recent stadium emergencies have demonstrated that there is a need to put occupant safety at the forefront of stadium design. In 2017, a bombing at a stadium in Manchester, UK resulted in 22 casualties and over 800 injuries (Snapes, 2018). The onset of mass egress caused particular difficulty with regards to evacuating the wounded from the grounds. Moreover, crowd crush accidents can result from unsafe stadium designs or poor operational management. In 1989, ninety-six individuals, ranging in age from 10 to 67, lost their lives at a stadium in Sheffield, England due to insufficient stadium capacity and poor management decisions (Bilefsky, 2017). A comprehensive list of stadium disasters can be found in the Appendix A1. Of the 20 historic stadium disasters involving fatalities, the source of 50% of these disasters were due to crowd crushes. Of the remaining disasters caused by either fire, fights in the crowd, weather incidents, acts of terrorism, or structural collapses, the majority of the deaths associated with these incidents were not due to the initial source threat of the disaster but to the mass onset of egress these caused, also resulting in crowd crushes.

One of the most notable and disastrous incidents in history is the Bradford Stadium fire which occurred in 1985. Right before half time, a small fire was noticed emerging from between the wooden stands. The cause of the fire is hypothesized to have been the accidental dropping of a cigarette under the stands and was fuelled by trash underneath the wooden stands. Within one minute, large flames were visible and police started to evacuate people in the stands. Only three minutes later, all the wooden stands on the side of the fire origin and the roof above were on fire and police struggled to save those who were too weak or stunned to escape. Fans stampeded to an exit which was locked, only for three strong men to throw their body weight against it in order to push it open. The death toll of 56 was due to a combination of some who succumbed to smoke inhalation and others who were subject to crowd crush. This death toll may have been higher had this gate not been forced open or had it not been for the courageous acts of the police offers who guided people out of the stands (BBC, 2012).

In summary, delivering crowd safety should begin in the design phase and adopt an approach that integrates design and management (Rowe and Ancliffe, 2008). Although the majority of this thesis does not analyze egress in the context of an emergency due to obvious ethical concerns, it is important to understand that normal egress performance is a baseline indicator of how efficient the stadium will perform in an evacuation.

1.5 Research Focus and Scope

The ultimate goal of this research study was to facilitate guidance for the application of MassMotion Software to stadium modeling and steer future research advancements into establishing the software as a multi-purpose pedestrian movement tool that can be used in a range building types (museums, care homes, stadia, etc.). The research presented describes novel data collection at Canadian stadia to provide further insights to practitioners regarding quantitative (egress times) and qualitative (observed behaviours) factors. The results of those experiments were analyzed and a MassMotion model for the performance of a stadium in normal egress conditions was developed and validated based on those tests. The goal for building the base model was to provide a platform for running predictive scenarios and allow it to be used as a benchmark for future stadium and design tool generation research. Once the influence of specified input parameters was determined, the research shifted to the evaluation of a stadium case study fire to assess whether the insights gathered during normal egress analysis held true in emergency conditions. It will be outlined what metrics may govern egress times of a certain stadium and allow practitioners to determine if the approach is applicable for their specific application.

Furthermore, this research focus aims to show why more human behaviour case studies need to be observed in order to create databases on certain behaviours that can be applied with confidence in evacuation models. Data on individuals with accessibility requirements was gathered as there is a need to increase the knowledge base and data available on individuals with mobility aids, which are required to be modeled during the stadium design process. This research regarding the data obtained on vulnerable populations addresses research needs and top priorities identified within the SFPE research roadmap framework (SFPE, 2018).

1.6 Research Objectives

The objectives of the research are as follows:

1) Collect two data sets of stadium egress data to inform and validate a stadium model;

2) Evaluate the influence of demographics on total egress times of the stadium under normal circumstances;

3) Provide insights based on the stadium fire case study and compare to localized stadium model output under localized emergency conditions; and

4) Tabulate a database of individuals that have accessibility requirements to provide data for customized agent profiles to be used in future stadium modeling where it may be needed.

1.7 Thesis Outline

This chapter introduces the reader to the topic, sets out the focus areas, and provides research objectives for the project.

Chapter 2 summarizes relevant background information and previous research required to understand the contributions of this research project. The chapter will cover the background information on human behaviour in fire, relevant past experiments, and related publications. Moreover, North American and International standards relevant to stadia design will be outlined. This is necessary in order to identify gaps in current practice and areas in need of research. Finally, a summary of the fundamentals of MassMotion software are outlined.

Chapter 3 discusses one of two experimental components of the project, which was conducted at a Canadian stadium to obtain a set of data on egress performance. The equipment used, filming positions, and filming procedures will be outlined. The filming methodology of this specific stadium will be discussed. Multiple trials were carried out the stadium in order to collect data and assess varying parameters in the same architecture.

Chapter 4 outlines the stadium model development and follows with validation of collected data from the experimental trials under normal conditions. The model development is explained in detail and the choice of parameter inputs are discussed. Various factors are assessed to ensure validation, including quantities and qualitative egress factors. Upon validation analysis, predictive scenarios are run to assess the impact of demographics on the stadium’s egress results. The chapter concludes with a discussion on various strategies to apply to assist in modeling stadia in MassMotion software.

Chapter 5 analyzes a case study fire that occurred at one of the stadia of interest. This allowed collection of evacuation data and analysis of egress under emergency conditions. The incident occurred after the researchers conducted and analyzed their data from the egress trials conducted under normal conditions. The analysis was done using publicly available video footage and information from the fire. The chapter provides a MassMotion model of the local stand area that the fire occurred in and compares agent behaviours to that observed to the occupants in the footage of the case study.

Chapter 6 provides an outline of the experimental trials carried out at a second Canadian stadium regarding accessibility concerns and the movement of disabled people. An introduction to accessibility in stadium design and the need for data regarding the movements of disabled bodies in stadia will be presented. The experimental methodology and test set-up for this stadium will be outlined in this report. A database of people with various 'visible' accessibility needs will be provided including but not limited to: those with electric mobility aids, mechanical mobility aids, oversized baggage, and families with young children. This database will be used as the foundation in future accessibility work which will follow this thesis contribution to allow the creation of customized agent profiles including the walking speeds of various mobility concerns.

This final chapter provides conclusions on the results of the study and explains how the multiple phased thesis will provide guidance on stadium egress design. Chapter 7 outlines how the conclusions may be applied by both practitioners and researchers in industry to provide confidence in modeling human behaviour in stadia during normal and emergency conditions. Following the seven main chapters, there is one appendix which includes any relevant further data that would interrupt text flow within the thesis itself.

Chapter 2: Background and Literary Review

2.1 Human Behaviour Research

This section reviews relevant human behavioural crowd studies, which will be followed by how these behaviours have shaped or been constrained by relevant design standards over time. The chapter will conclude with a brief overview of MassMotion software and provide background behind the software's algorithms and default settings. Prior to outlining previous research and background, it is important to define some key terms intended for accessibility of this thesis. The term egress refers to the means of exiting a designated area (Merriam-Webster, 2019). The term egress can be applied in a non-emergency context and in the context of an emergency such as an evacuation due to fire. The total time an individual takes to egress can be broken down into several phases as displayed in Equation 2.1. The phases in italics are relevant to an emergency situation only and all remaining phases are relevant to egress under both emergency and normal conditions.

$$\text{Total Egress Time} = \mathit{Time\ to\ Alarm} + \text{Time to recognition} + \text{Premovement time} + \text{Movement time}$$

Equation 2.1

The time to alarm, specific to emergency situations, is the time in which an alarm takes to detect the incident and sound. In the case of a fire, this would be the time between when a fire starts and when the alarm detects the smoke and sound. The time to recognition can be defined as the time between which the alarm sounds and the individual recognizes the sound. In a non-emergency context, this could be the game buzzer after a sporting event for example, or any point in time when the service being provided in a venue has come to an end. The premovement time is defined as the duration of time between the time to recognition and the time they begin physically moving towards their exit of choice in an attempt to egress or evacuate. Finally, the movement time is the time a person spends after their initial point of movement until they have reached a designated exit. All the aforementioned phases can be summed to determine the total egress time of that individual.

Egress time is influenced by a number of factors, both physical and non-physical. Some notable physical attributes that are important to define include walking speeds and human radiuses. A walking speed, or gait speed, is the distance walked during a certain period divided by the time taken to walk that particular distance (Whitney, 2016). This speed can be affected by an individual’s height, weight, age, culture, fitness level, and the terrain quality and slope in which the individual is walking on. Another physical term used in egress analysis is anthropometry which involves various systematic measurements of the human body (Dictionary, 2019). This term in the context of egress analysis is important when looking at the radiuses of people and the widths they require on an egress route or path. Furthermore, there are also radiuses in which people impose between themselves and others, which can be influenced by cognitive actions. Physical actions and egress behaviours can be influenced by cognitive biases that influence an individual’s judgement and decision-making. This could include how much space a person may want to leave between their own body and another person, which may be influenced on how well they know other individuals and how external groups are moving around them (IDF, 2012).

2.1.1 Dynamic Individual and Group Behaviours

Evacuation modeling is currently limited in its ability to consider cognitive actions. This is problematic as experimental studies have shown that similar crowds behave differently when they identify with a group or have a psychological connection to other group members (Templeton et al., 2015). Such findings were exhibited in a study carried out which examined 140 crowd studies, which all met the inclusion criteria of containing simulations of crowd events taken from footage in real life scenarios and assessed the effect of crowds for events using computer. Only twenty-four, or 17%, of these studies considered cognitive or group identifiers in modeling (Templeton et al., 2015). In order to model crowd behaviour realistically, simulations must use methods which allow crowd members to identify with each other. Modeling this dynamic interaction between evacuees with one another and staff is necessary to reduce uncertainty when it comes to modeling such evacuation events. Factors in which these cognitive connections influence egress include but are not limited to radiuses in which people impose between themselves and others, as well as walking speeds.

Another study on conceptualizing collective behaviours identified that a shared sense of social identity between participants resulted in more coordinated and constructed movements amongst a group (Templeton et al., 2018). It was observed that psychological crowds, or groups which are aware of having a personal connection to others in the group, maintain a closer proximity or radius to other members in their group regardless of the total number of people in the area. Another finding was that having a group social identity didn't only affect the behaviour of those in the group but also the movement of external individuals who were not part of the psychological crowd (Templeton et al., 2018).

In addition to personal behaviours, people will be influenced by what other external members, such as authoritative figures, tell or direct them to do. During the pre-decisional process of an evacuation, cues play a large role in an evacuee's decision (Gwynne et al., 2015). The more clearly a cue is presented, the more probable it will accurately be understood and followed. This implies that even if a threat is apparent to the evacuee, movement towards egressing may not be made until a clear and precise cue is directed towards the individual.

Furthermore, a number of human behaviour studies were done in the 1970s and 1980s by Jake Pauls, then of the National Research Council of Canada (NRC). Pauls' three most prominent studies include investigations at stadia in Canada: Olympic Park in Montreal, the Commonwealth Stadium in Edmonton, and The Exhibition Stadium in Toronto (Pauls and Johnson, 1977; Pauls, 1982, 2007). All of these studies included large crowds which were filmed to observe behaviours in order to study the safety and usability of the stadia. These studies were completed prior to the development of computational tools and the majority of videos from these studies are lost. These studies raised some important arguments relating to the egress of patrons, including that unrealistic egress estimates and misconceptions about crowd flow have been long accepted by designers and safety officials, knowledge of safety implications are limited, and that standards of safety were not explicitly established.

Pauls' first study was conducted at Olympic Park in Montreal, Quebec in 1976 (Pauls and Johnson, 1977). Pauls along with 10 NRC staff filmed crowd behaviour using 13 Super-8 film cameras that were directed at the aisles of three stands. The main findings from this study revolved around flaws in the architecture of the stadium, including non-uniform heights of stairs and the inefficient placement of covered roofs to shelter patrons during rain.

The second study was conducted during the 1978 Commonwealth Games in Edmonton, Alberta when Pauls and six filming assistants conducted a study of people moving on the stairs in the Commonwealth Stadium. This study focused on individual movement and body sway as people walked up and down the stairs of the stadium. The data collected from this study regarding aisle stair widths contributed to the United States building codes, adopting the 1200mm clear stair width requirement for aisle stairs (Pauls, 2007).

The third study focused on a rock concert held at Exhibition Stadium in Toronto, Ontario on July 16th, 1980 (Pauls, 1982). The motivation for this study came from two tragedies that had occurred in years prior at a soccer match in Scotland and a rock concert in North America. Both events resulted in fatalities due to improper crowd control. Due to the high expected attendance of the concert, representatives from the City of Toronto and the show manager reached out to Pauls and asked that the NRC conduct a study at their upcoming rock concert in the hopes of establishing safety guidelines for future rock concerts hosted there. The attendance of the concert was 70,000 at the it's peak, with 30 to 35 thousand on the field and 35 to 40 thousand in the grandstands. Pauls and the assistants observed the crowd behaviour at the game using a Super-8 film camera, photographs, audio tapes and written records. He found poor crowd management conditions, particularly inconsistent ticket checking upon entry, and the inability of the stadium to control the crowd when they began to create a crush towards the front of stage. The crush towards the front of the stage created dangerous conditions where the only way spectators could get out of the crowd was to be pulled out near the front of the stage. Certain egress route conditions were subpar, including paths that were not properly lit and a lack of signage that caused patrons to mistake a regular barrier for an egress route. From this study, Pauls made recommendations to control how the crowd was let into the stadium and to reduce the crowd density on the field and maintain convenient circulation routes near the stage. Suggestions were also made to improve lighting conditions, to alter the design of the stage to create better sightlines for patrons, and to install CCTV cameras in order to make the back of the crowd aware of any crowd crush conditions at the front of the crowd.

2.1.2 Queuing Behaviours

Another factor affecting crowds in stadia is that people are subject to queues and their associated waiting times. It is important to understand the psychology behind people waiting in queues and the way in which being at a standstill can affect people mentally and physically. The experience of waiting in a line in a service facility affects the perception of the quality of service being provided (Maister, 1985). In the case of stadia, an example of the 'service' being delivered would be the viewing of a sporting event, with the 'waiting time' being ticket checks, security checks, or in slow moving crowds during ingress or egress. Waiting can be frustrating and time consuming to a consumer (Maister, 1985). The psychology behind wait times relates to the basis of the First Law of Service as displayed in Equation 2.2 (Sureshchandar et al., 1993).

$$\text{First Law of Service: Satisfaction} = \text{Perception} - \text{Expectation } [S=P-E]$$

Equation 2.2

There are various aspects of stadium operations that can affect the overall perception of the experience, and ultimately the satisfaction of spectators. The aspects of waiting times can be assessed in the context of stadium queues during ingress and egress and whether there are aspects of stadium design which could assist people in being prepared to wait longer. In the context of pedestrian queues, it is a well-known theory that occupied time feels shorter than unoccupied time (Maister, 1985). To draw attention away from the passage of time, the following questions could be asked in the context of stadia:

- Can any aspect be added for spectators queuing to do or view that will speed up the service time once inside the venue?
- Can any activity be offered to queuing spectators that will add an additional revenue facet?
- Can you utilize lighting or sound effects to entertain queuing spectators?

With these questions in mind, it is important that the additional ‘filler-activities’ are of additional benefit and are in relation to the service provided. Adding activities non-related to the service can be of annoyance and cause irritation (Maister, 1985). For sports events, these filler-activities could include handing out game brochures, announcing game and player statistics on the loudspeaker, and having queue TV’s that display the players warming up on the field or game statistics (Maister, 1985).

Offering service related filler-activities also convey the message that the service has already started. A pre-process wait feels longer than an in-process wait. In the case of stadia, adding filler-activities in line will make spectators feel as though they are already part of the experience as opposed to waiting to become a part of it and potentially developing feels of anxiety or stress (Maister, 1985). A main reason peoplve feel the need to ‘get started’ in their experience is to prevent anxiety. Having multiple lines to choose from often causes stress as people have to choose which line to wait in, resulting in the effect “the other line always moves faster” (Maister, 1985). Additionally, reassurance that the line is moving fast enough and spectators will be able to make it to their service on time minimizes anxiety. It is important to consider what customers may be rationally or irrationally worrying about and what management can do to ease this.

Being informed of realistic or overestimated wait times in advance manages customer expectations (Maister, 1985). This can be applied to stadia by having queue wait times for ingress and egress routes requiring queueing such as coat checks, ticket checking, or security. This perceived wait time could be minimized by methods such as screens displaying the wait time or showing the number or people in line and the rate at which its progressing. An explanation may or may not ease customer’s anxiety, but it is better than no explanation at all. Waiting in ignorance makes customers feel powerless which typically results in customers being rude as they attempt to reclaim their status as paying customers (Maister, 1985).

Tolerance for waiting can be increased with perceived value. For this reason, post-process waits always feel longer than pre-process waits or in-process waits. After a service is over, the value gained is over and any post-process time required will typically not be tolerated by customers. This applies to the egress of stadia after an event as spectators do not want to be held up in crowds. People desire efficient routes from their seats to their parked car. This also applies to the parking lot of a stadium, where unorganized traffic situations could dampen a positive game experience. Post-process queuing will feel longer to spectators, despite the actual wait time itself (Maister, 1985). Additionally, research shows solo waiting experiences feel longer than group waiting times, despite actual wait time occurred (Maister, 1985). This can be mitigated in stadium queues by implementing methods to promote a sense of group waiting rather than isolating individuals. This may be achieved by widening a queue to allow parties to stand two by two rather than one by one. Also, having team statistics on screens and announcements could encourage bonding conversations between people waiting.

2.1.3 Walking Speeds

There have been several experiments undertaken to assess the relationship between density and walking speeds. Studies have been conducted under various circumstances and some notable experiments include those in public buildings (Predtechenskii and Milinskii, 1978) along walkways in the New York Subway stations (Fruin, 1971) and in railway stations (Ando, K. et al., 1988; Bae et al., 2014). Of these studies, Fruin’s findings are commonly applied in the context of egress computational and numerical simulations. Fruin’s results are based on speed and density data collected in the New York subway in the 1970s for commuters during general circulation. The main limitation with the Fruin study is that it does not have an available demographic breakdown, but rather applies a nominal distribution of a single walker speed to represent movement, which is used to randomly assign a speed for all agents.

Of the notable studies listed above, Ando analyzes the deviation in normal walking speeds between various age groups. This study provides a mean and range of speeds for children (<18 years old), young adults (19-36 years old), adults (37-65 years old), and elderly (>65 years old). The minimum and maximum walking speeds observed in these ranges were 0.6 to 1.7 meters per second (Ando et al., 1988). Limitations to Ando's study include that there was not an in-depth explanation as to how the walking speeds and parameters were derived. Although commonly cited across human behaviour studies, Ando's study was originally written in Japanese and no English version of the manuscript could be attained at first. The author of this thesis had the manuscript translated and found the only explanation as to how the behavioural data was derived was from "various architectural studies", with no further details as to exactly what was observed to obtain this data collected in the study.

2.2 Relevant Egress Standards and Guidelines

2.2.1 International Egress Standards

The Guide to Safety at Sports Grounds, commonly known as The Green Guide (SGSA, 2018), was developed to be used by professionals globally for the design and management of safety in sports stadia. The Green Guide addresses safety management protocols with an emphasis on giving responsibility to management to undertake its own risk assessments on the safety of its spectators. It advises on fan behaviour taking into consideration demographics, event type, counter terrorism tactics, any many other factors. In The Green Guide, there are various ‘minute’ rules that are used for guidance in planning for pedestrian egress. Such guidance specifies finite durations in which all spectators should be able to exit from a specific area of the stadium under normal and emergency conditions.

2.2.1.1 Normal Conditions

One acceptance criterion for stadium architecture outlined in The Green Guide mandates that all occupants should be able to egress from a stadium in eight minutes under normal conditions (SGSA, 2018). The case behind this eight-minute rule applied to stadia lacks qualitative basis with only a brief explanation regarding that is based on minimizing a person’s stress state in crowds. Investigation into the underlying guidance, by the thesis author, revealed that it was formulated from photographing and videotaping the crowds during fifteen soccer matches at eleven different stadia in the United Kingdom (Poyner, 1972). The eight-minute benchmark was first officially published in the 1972 SCICON report as the seven-minute rule stating that in durations longer than seven minutes the pressures in the crowd and movement through an exit becomes severe (Poyner, 1972). This crowdedness caused visible anxiety and stress to people involved in the crowd. Beyond the brief and insufficiently detailed SCICON report, there is no other public domain data known to be applied in the development of this rule. The rule appears to have been arbitrarily assigned.

Research from the SCICON report was incorporated into The Green Guide. Examination of the rule from the 1973 first edition to the 2018 sixth edition of The Green Guide illustrates that in the most recent version the guidance states: “The limit of eight minutes has been set as a result of research and experience, which suggests that within this period, spectators are less likely to become agitated, or experience frustration or stress...” (SGSA, 2018). It is important to emphasize that this guideline pertains to normal egress and not to that of an emergency evacuation, which the Green Guide speaks to separately.

Furthermore, the sixth edition contains an extension of management responsibilities to spectators at the facilities including the need for a risk assessment for all events, including pre or post event entertainments. Booths or other non-typical architectural changes to the stadium associated with pre or post event entertainment have potential to impact the normal egress times. The addition of these required management responsibilities will provide further risk mitigation measures that were not mandated in the fifth edition (SGSA, 2018).

The sixth edition has also included guidelines for concourse design and management. These guidelines provides further confidence to the determination of normal egress times, as improperly planned or managed concourses can significantly affect exit route capacities and flow rates. The sixth edition provides many additional and more specific densities for modelling and verifying concourses levels which could improve parameters for crowd modelling.

2.2.1.2 Emergency Conditions

In the context of emergency conditions, examination of the rule from the 1973 first edition to the 2018 sixth edition of The Green Guide illustrates that today the guidance states: “Note also that the maximum time it should take a spectator to travel from his or her seat, or place, and reach the start of an exit route, is […] between two and half and eight minutes under emergency conditions” (SGSA, 2018). The variance in time depends on the level of fire risk inherent. According to the Green Guide’s standardization process, a stadium’s fire risk is dependant on what sections of the stadium are exposed to the outdoors, the quantity of combustible materials present on the egress route, and the magnitude of the risk of fire spread. For example, a "medium" or normal fire risk ranking places the recommended emergency egress guideline at five minutes.

For the example provided, the emergency egress time calculation is used to determine the capacity of the emergency exit system from the viewing accommodation (Zone Two) to a place of reasonable safety, or a place of safety (Zone Five). The relative orientation of these zones are displayed in Figure 2.1, in which zone two is defined as the spectator viewing accommodation and zone five is a buffer zone outside the sports ground permit (SGSA, 2018).

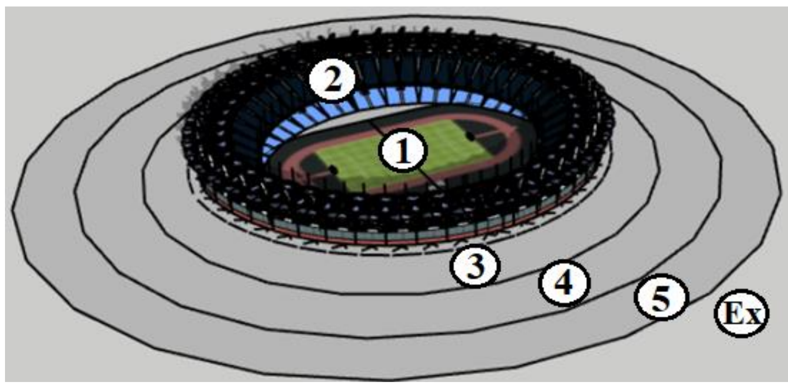

Figure 2.1: Depiction of egress zones for emergency conditions according to the Sixth Edition of the Green Guide

2.2.2 Canadian Egress Standards

Although the Green Guide is used internationally, the guidance baseline followed in Canada, where the stadia studied in this thesis are located, is the National Fire Protection Association Code 101 (NFPA 101) which contains documentation for means of egress for buildings and structures (NFPA 101: Life Safety Code, 2018). Large stadia are typically designed in accordance with the "smoke protected seating" provisions of NFPA 101, which requires that patrons can clear the seating area and reach an egress concourse in a certain amount of time. These permitted evacuation times are based on a linear relationship between number of seats and nominal flow time, with not less than 3.3 minutes for 2000 seats plus 1 second for every additional 50 seats up to 25,000. Beyond 25,000 total seats, the nominal flow time is limited to 11 minutes. Nominal flow time refers to the flow time for the most able group of patrons, as some groups are less familiar with the premises or less able groups might take longer to pass a point in the egress system. NFPA also states maximum permitted travel distances to exits from the point in which the spectator has cleared the seating area and has reached an egress concourse, which dictates the overall evacuation time for the stadium.

2.3 MassMotion Egress Modeling Software

MassMotion[1] was chosen as a software of choice as it is commonly used by practitioners for egress and crowd flow analysis. Although it is currently not the most widely used, it is an appropriate selection for the modeling in this thesis as MassMotion has not been extensively tested in the context of stadia and therefore the need for validation for such applications exists. Further use of MassMotion for simulation analysis in combination with validation experiments will allow for recognition of areas the software is strong in but also areas in which it can be improved. The software entails a variety of tools for creating and modifying 3D environments, defining operational scenarios, executing dynamic simulations and developing powerful analyses. A summary of some important default agent parameters and their derivation will be provided below. Further summary on basic user features are summarized in Oasys's Manual on Verification and Validation of MassMotion (Kinsey et al., 2015).

[1] Version 9.5

2.3.1 Default Agent Speeds

The default agent speed and radius profile for MassMotion is the Fruin Commuter, which is based on the data collected by John Fruin as aforementioned in Section 2.1.3 of this chapter. Every agent in MassMotion has a randomly assigned natural walking speed. The default agent speeds are normally distributed in a range from 0.65 to 2.05 meters/second with an average of 1.35 meters/second and a standard deviation of 0.25 meters/second. Agents adjust their speeds based upon congestion as well as the type and slope of the surface being traversed. Based on Fruin's observed speeds, MassMotion assigns agent stair speeds as a function of the horizontal surface walking speed, and naturally the speed of the agent is reduced as the slope of the traverse gets steeper (Rivers et al., 2014).

2.3.2 Social Forces Framework: Agent Movement and Decision Making

MassMotion's crowd movement calculations is based on a social forces algorithm originally based on the social force framework founded by Helbing. Helbing's original framework, founded in 1995 and archived in 1998, places pedestrian behaviour into equations of motion in the form of nonlinearly couple Langevin equations (Helbing and Molnar, 1998). These equations represent formulas of acceleration and deceleration as a reaction to perceived information received from their surrounding environment. The vector quantity is a representation of the social force based on environmental changes and preferred velocities of the agents. Agents adjust their movement patterns in response to these various social forces, in order to avoid obstructions and collisions with other agents (Helbing and Molnar, 1998). Figure 2.2 shows a visual depiction of a few of the main social forces in MassMotion and how they interact with one another. The green arrow is an attractive force, which pulls an agent towards a specific target or goal location. The yellow arrow is a repulsive force between neighbouring agents in order to maintain designated spacing and avoid collisions. The brown arrow represents a repulsive drift force that moves agents away from other oncoming agents towards their preferred side, set by the modeller. The black arrow is the resultant velocity, which is the vector sum of all the combined forces.

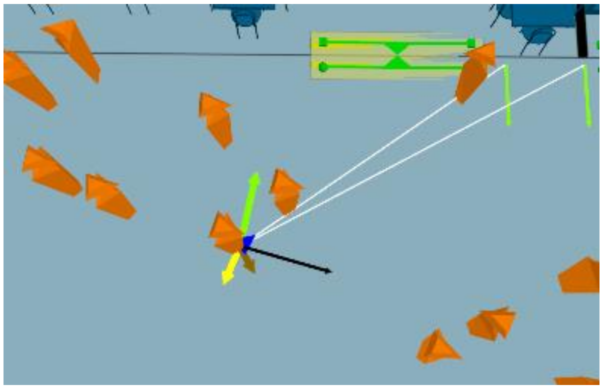

Figure 2.2: Social Forces in MassMotion

The social forces also involve network path planning between agent's intended origins and destinations. Agents will analyze distance, terrain geometry, congestion, and develop corresponding costs for routes available to the agent's goal, ultimately selecting the path with the minimized cost. The simplified equation for total route cost in MassMotion is provided in Equation 2.3 (Rivers et al., 2014).

$$Cost = W_D * \left(\frac{D_G}{v}\right) + W_Q * Q + W_L * L$$

Equation 2.3

where W_D is the distance weight, D_G is the total distance from agent position to ultimate goal, v is the agent's desired velocity, W_Q is the weight of the queue, Q is the expected time in queue before reaching link entrance, W_L is the link traversal weight and L is the link type cost (level, ramp, stair, etc.). Here, W_D, V, W_Q, and W_L are randomly applied to agents from a distribution (Rivers et al., 2014).

2.4 Conclusions

There have been numerous studies dating back decades on the various complexities of human behaviour. The background information and literature review provided indicates that there are still many gaps in the knowledge. Variance in architectural geometry coupled with the variability in human behaviours results in a large number of potential scenarios for human behaviour research to be conducted within. The ability to design structures with efficiency while ensuring safety relies on strong knowledge of the potential behavioural outcomes which has still not been researched extensively in areas such as stadia. Furthermore, the designs for stadia in Canada and internationally would benefit from validated numerical models to defend crowd modeling software used in the design process of stadia.

Chapter 3: Stadium Egress Performance Under Normal Conditions

3.1 Introduction

The main goal of considering a stadium study in Canada is to observe the movement of people during ingress and egress in stadium seating areas before and after a large event. The novelty of the data set collected from this stadium of interest is similar to Jake Pauls' research at the Commonwealth Stadium in Edmonton, Olympic Stadium in Toronto, and Olympic Park in Montreal as outlined in Chapter 2, but focuses on qualitative factors such as total egress times (Pauls and Johnson, 1977; Pauls, 1982, 2007). This chapter serves to report the experimental data collection at one Canadian stadium of interest in which trials were conducted. Although anonymity was not requested, the identity and exact location of the stadium have been kept anonymous by the thesis author due to the sensitive nature of the research. The methodology of the data collection at a second stadium will be outlined in Chapter 6, as the goal of that second stadium was to focus on accessibility data collection as opposed to total egress times. The case stadium of this chapter had very restricted filming views, limited by the stadium managers, which made an accessibility study difficult. The second stadium focused in on in Chapter 6 was less restricted in terms of locations to set-up filming, which offered better views that allowed pedestrian movement in and around the stadium. The second stadium also offered the ability to film over the course of several days, with events running all day long, as opposed to the first stadium which was focused on two single events. The study in this chapter is aimed to further investigate the context and applicability of egress benchmarks such as the "Eight Minute Rule" being applied in a contemporary stadium design. The scope of work for this first experimental phase includes novel data collection in order to provide confidence for simulated crowd models.

3.2 Experimental Methodology

3.2.1 Experimental Overview

This chapter considered two egress trials with crowds of over 20,000 people, carried out at a contemporary Canadian stadium. The stadium is home to national sporting events, in which these sporting events were ongoing during the egress studies. Preliminary trials were conducted to test equipment and trouble shoot filming methods in order to prepare for the two main filming studies.

Experimental trials took place in fall of 2017 where the stadium seating stands were open to the environment, while most of the egress routes were roofed and enclosed on two sides. High resolution cameras were strategically placed to observe crowd conditions in the stands, egress paths, and were able to capture facial expressions of pedestrians. Filming locations were performed in accordance with allowances provided by the stadium and event managers, therefore some angles and data were not possible to collect. This study considered factors with potential to influence behaviour including the game score, weather, and demographics by performing multiple trials at the same stadium. Data was collected for all these parameters, but due to the scope of the thesis only certain parameters were able to be analyzed and assessed, in which remaining parameters will be analyzed in future work.

3.2.2 Stadium Architectural Layout

The stadium of interest has a capacity of 24,000. The stadium, originally constructed in the 1960s, was renovated with modern upgrades in 2014 which involved revitalization of the existing north stands and construction of new south stands. Figure 3.1 shows the general layout of the stadium, with the three main exits being Gate 1, the North Walkway, and the East Bridge. In order to keep the stadium anonymous, a map of the rendered stadium was used in which the development of the model will be explained in Chapter 4. Gate 1 provides the highest capacity of exit width at 27.9 meters, followed by the North Walkway at 7.1 meters and the East Bridge at 2 meters. It is important to note that these were the exits encouraged and advertised for use through ushers and signage during normal egress, and that other doors are provided around the stadium for emergency situations.

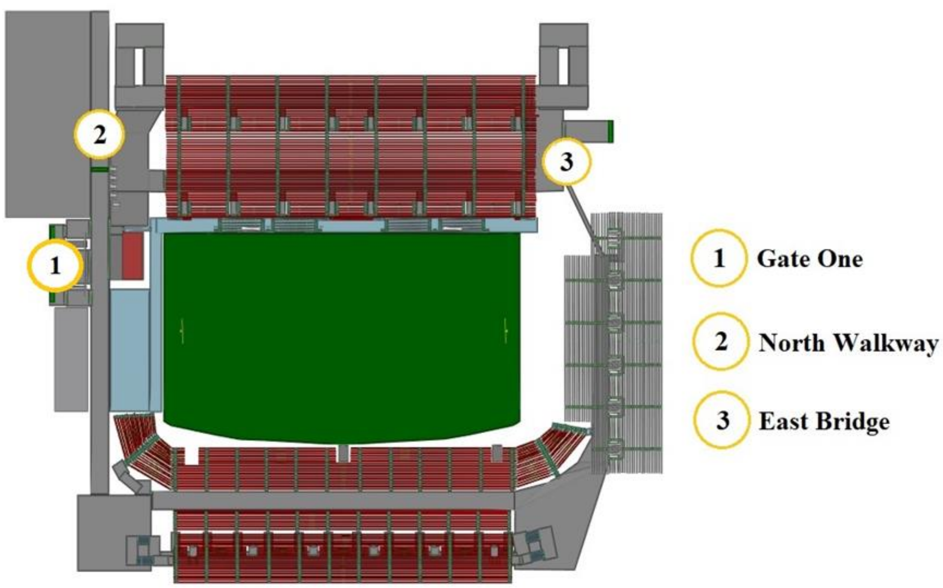

Figure 3.1: General Stadium Architectural Layout

3.2.3 Filming Equipment

The cameras used include a Canon EOS 5DS (50.6 megapixels), Canon EOS 5D Mark III (22.3 megapixels), and two Canon Rebel T6 cameras (18 megapixels)[2]. Each camera sported a 24-105mm lens. A Canon EF 70-200 mm (F/2.8L IS II USM) zoom lens was also used for one of the two trials. All cameras were mounted on compatible, high quality tripods. Two spare batteries for each camera were brought to the stadium in order to ensure enough power was available for the entire filming duration. One charger for each camera was brought to site in order to charge batteries when required. Each camera also had two 128 GB memory cards allocated to it for storage, totaling 8 memory cards for the project. To keep information organized, one memory card was used for ingress and one for egress filming.

3.3 Main Filming Trial One

3.3.1 Trial One Overview

The first main filming trial was carried out during a North American sporting event with 21,965 attendees, which represents 92% of stadium capacity. This attendance number was reported verbally to the researchers by the stadium manager after the event, which was based on the number of actual people that were checked into the stadium through their ticket stub for the event. All three stadium exits were available and open for use by spectators as displayed in Figure 3.2. Heavy rainfall and winds occurred during the entire egress duration. Researchers set-

[2] The various camera types were what were already available in terms of equipment in the author's research team. Outside this project, these cameras are used for structural deformation measurements and therefore some of the cameras required are different in specifications for those certain applications. The various camera types have minimal impact on the study herein.

up equipment 1.5 hours prior to the start of the game to ensure cameras were positioned before the gates opened for ingress. Cameras were turned on 10 minutes prior to the gates being opened for ingress into the stadium, which was one hour prior to the game start time. Researchers stopped filming ingress approximately 6 minutes past the start of the sporting event, a point in time in which there no longer standing queues to enter the stadium upon ticket checkpoints. Complete analysis of ingress footage is beyond the scope of this current thesis and is reserved for future work.[3] Researchers took a filming break after ingress while there were no crowds flowing in or out of the stadium to charge batteries that needed to be charged. The criteria used to identify the onset to film egress was the point in time in which 100 occupants had left the stadium over a period of three minutes. This point in time occurred approximately 27 minutes before the final game buzzer. The thesis author acknowledges this measure is arbitrary but was applied to both experimental trials. This arbitrary measure to identify initial egress identification point has no impact on the data analysis or research results. Egress filming was stopped upon notice that all those that were attempting to egress from the stadium after the game had done so. This did not consider those that stayed for the stadium's "Fans On the Field Program" in which spectators were welcomed to linger around in order to be ushered onto the field after the game for activities. It was evident that these attendees were not making movement towards the exit, with many remaining in their seats, and were easily distinguished from those with intention to leave.

[3] Ingress analysis in terms of total ingress times was completed and such graphs can be found in Appendices A5 to A8. This was done for the purpose of assessing the gate utilization found in Figure 3.7. Filming of the North Walkway was not permitted due to angle-limitations in Trial One. The number assumed to be ingressing through this gate was based on the number of people ingressed through Gate One and the East Bridge subtracted from the total attendance numbers.

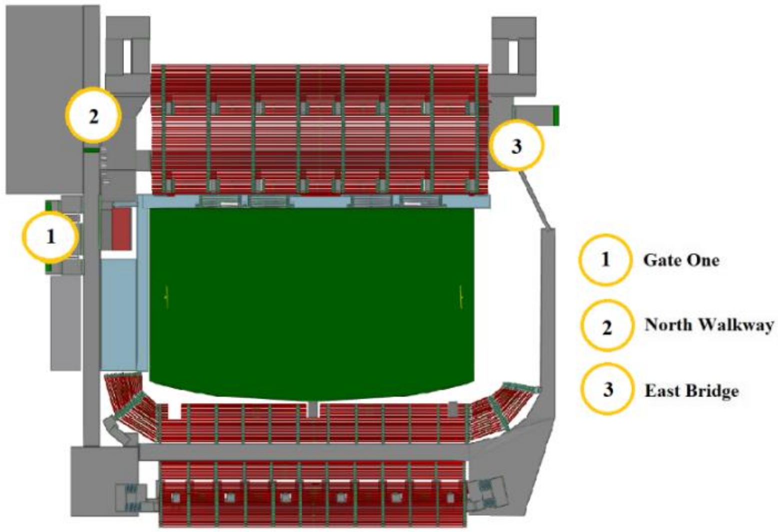

Figure 3.2: All Gates Open for Ingress and Egress in Trial One

3.3.2 Trial One Filming Set-Up

As seen in Figure 3.3, cameras were distributed over the stadium's three available exit points. Cameras were also positioned to capture the stands, including the egress routes which spectators took to reach the exit from their seat. The Canon EOS 5DS (50.6 megapixels) and Canon EOS 5D Mark III (22.3 megapixels) were placed at locations 2 and 3 respectively in Figure 3.3, on the inside vantage points closest to the stands to leverage the higher resolution cameras to capture the stands on the other side of the stadium. The two Canon Rebel T6 cameras (18 megapixels) were placed at locations 1 and 4 in Figure 3.3, on the outer vantage points of the ramps in order to capture the egress routes. Locations 1 through 4 are all located on the top level of the ramps existing on the north side of the stadium. The top ramp was chosen in order to maximize sightlines into the stadium.

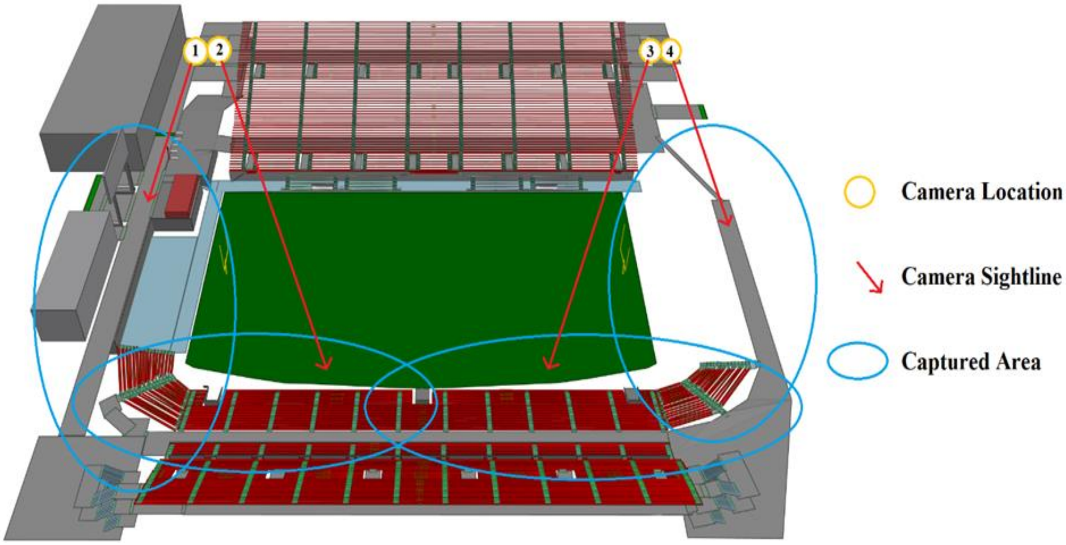

Figure 3.3: Trial One Camera Sightlines

3.4 Main Filming Trial Two

3.4.1 Trial Two Overview

The second major trial was carried out at the same contemporary stadium, during a similar game at 97% capacity or 23,280 attendees. This attendance number was recorded in the same manner as Trial One, it was communicated verbally to the researchers by the stadium manager after the event. The attendance was based on the number of actual people that were checked into the stadium through their ticket stub for the event. The East Bridge was closed for ingress and egress as indicated by the red mark in Figure 3.4, because the surrounding area was under construction to erect the temporary stands which would be used for an upcoming major event to expand the stadium capacity temporarily. These stands would add another 12,000 seats which represents a 50% increase in stadium capacity. This exit closure permitted spectators to egress through only the two other exits: Gate 1 and the North Walkway. This trial presented an effective worse-case scenario due to the exit closure, as stadium egress requirements must still be achieved in such events. The game score was extremely close until the last second resulting in a large crowd gathered near Gate One in the last few minutes to catch the end of the game. In contrast to the first trial, the skies were clear and no rain occurred throughout the event. The same filming procedure in terms of set-up times before the game were carried out as Trial One. However, the onset of egress occurred earlier then Trial One relative to the game buzzer, in which researchers began egress filming about 53 minutes prior the final game buzzer. Again, this trial did not consider those that stayed for the stadium's "Fans On the Field Program" and stopped egress filming upon notice that those who were making movement towards an exit had left the stadium.

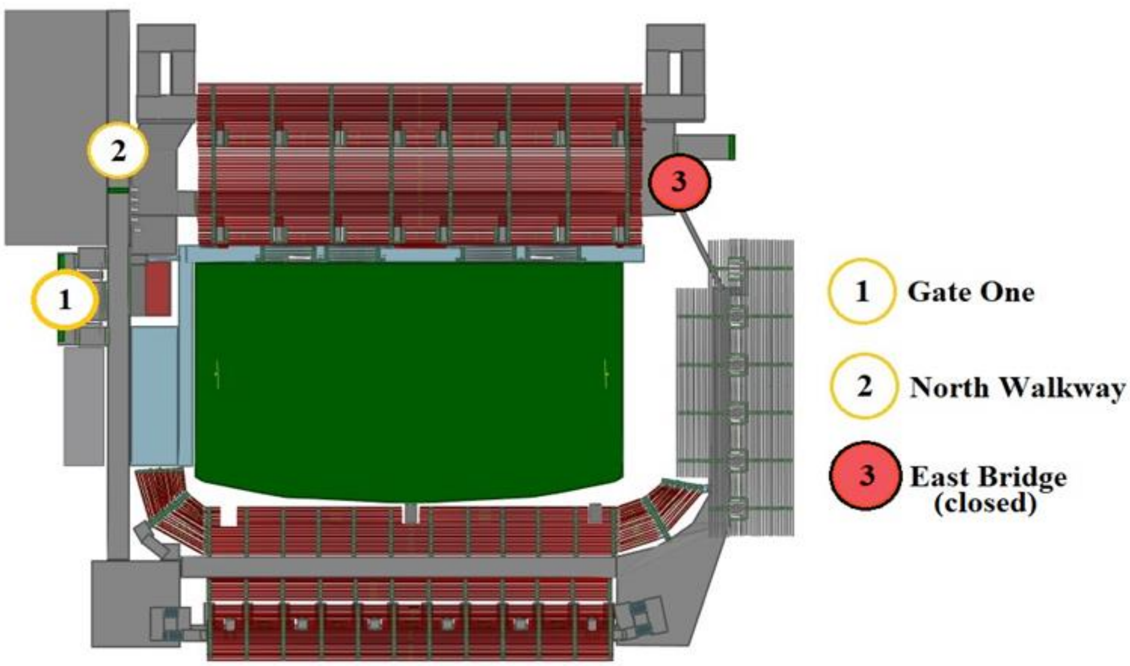

Figure 3.4: East Bridge Closed for Ingress and Egress in Trial Two

3.4.2 Trial Two Filming Set-Up

As seen in Figure 3.5, cameras were distributed over the stadium's two available exit points. The Canon EOS 5DS (50.6 megapixels) was placed at location 3, on the inside vantage point closest to the stands to leverage the higher resolution, to capture the stands on the other side of the stadium. The Canon EOS 5D Mark III (22.3 megapixels) was placed at location 1 to capture Gate 1 and the egress path leading from the south stands to Gate 1. One of the Canon Rebel T6 cameras (18 megapixels) was placed at location 2 to film the North Walkway and the egress route leading up to it. For this trial, a Canon EF 70-200 mm (F/2.8L IS II USM) zoom lens was used to observe the crowd behaviour in the denser areas and walkways to search for signs of agitation, frustration, or stress. One researcher walked through the stadium egress pathways during egress with this camera. This camera also allowed the researchers to obtain footage clear enough to distinguish game demographics.

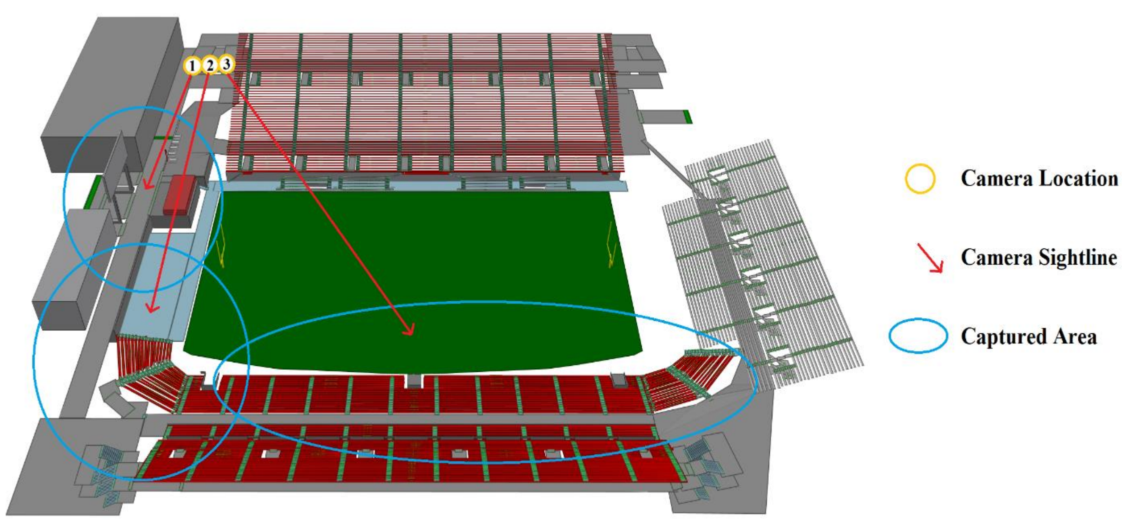

Figure 3.5: Trial Two Camera Sightlines

3.5 Experimental Data Analysis

The footage collected from experimental trials was securely transferred from camera memory cards to two Seagate Backup Plus Slim 4TB external hardrives, one for primary use and one for the purpose of backing up data. The two external hardrives were stored in a secure cabinet, in which only two primary researchers on the team had access to. Data analysis was conducted through use of a software developed by Arup Fire called Human Factors Analyser. This tool allows users to record event time data collected through video footage. A visual of the software interface is depicted in Figure 3.6.

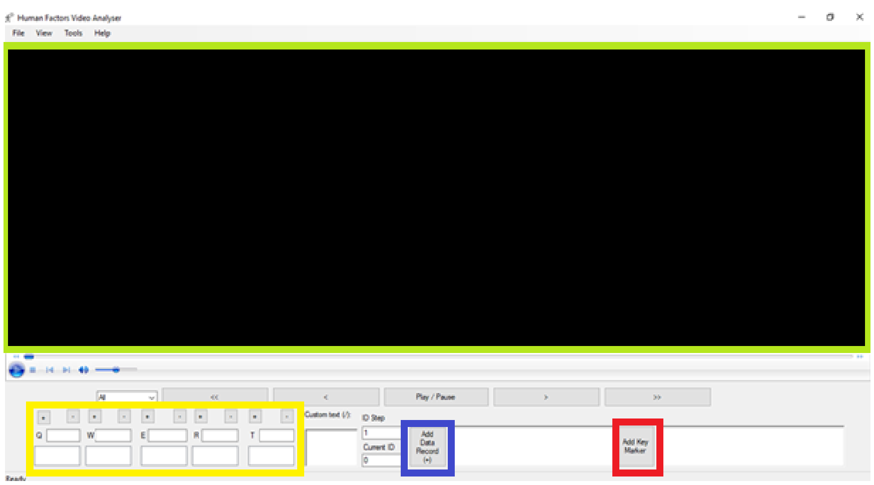

Figure 3.6: Human Factors Analyser Interface

This software enabled the people on the video footage to be tabulated in an organized manner. Footage of a certain gate would be uploaded to the black window outlined in green in Figure 3.6 The buttons outlined in yellow allowed the user to enter features about an individual on the footage, such as female or male. This feature was used when it came to establishing the demographic distribution of the event. When the "Add Data Record" button, highlighted in blue, was pushed manually by the user, the software would associate the data point with a corresponding timestamp from the footage. This allowed a collection of data points of people egressed over time in each piece of video footage that was focused on a gate. The "Add Key Marker" button outlined in red was to mark when the buzzer sounded at the end of the game, which allowed the author to more clearly find this emphasized data point compared to all the people that were counted using the "Add Data Record" button. People count was selected as a parameter of interest because it allows the user to compare the total counts through each gate and flow rates to those of the simulated trials which will be outlined in Chapter 4. Since all video footage will be kept and stored securely, future work could include re-visiting the footage and analyzing the data again should any improvements be made to the analysis software used which could improve the accuracy of data analysis.

3.6 Trial One and Trial Two Experimental Results

3.6.1 Gate Utilization

The gate utilization for ingress and egress for each event was reviewed and summarized in Figure 3.7. The percentage of people that used a specific entrance for ingress aligned within 5% to those that egressed through that exit. This attests to the commonly known philosophy that people tend to leave a building the same way they entered, even if the route is a less efficient alternative. Such behaviour manifests itself in people as studies show that individuals prefer the known over the unknown (Sime and Kimura, 1988). This emphasizes the importance of familiarity with exit routes or the application of signage to promote their usage. Furthermore, it was observed that upon closure of the East Bridge, approximately 75% of spectators chose to egress through Gate 1, which is over double the utilization when compared to the utilization of Gate 1 in Trial One. It would have been logical to predict that the North Walkway would have been the alternate route of choice for those originally intending to use the East Bridge since these exits lead out to the same side of the stadium and thus the same facilities such as parking locations. This implies there are other factors at play behind spectator's egress route choice, such as the reluctance to queue upon exiting as the North Walkway was subject to standstills and reduced flowrates after the game. Spectators migrated towards the wider exit, Gate 1, which provided an additional 20.8 meters greater in exit-width capacity and therefore reduced potential for bottlenecking.

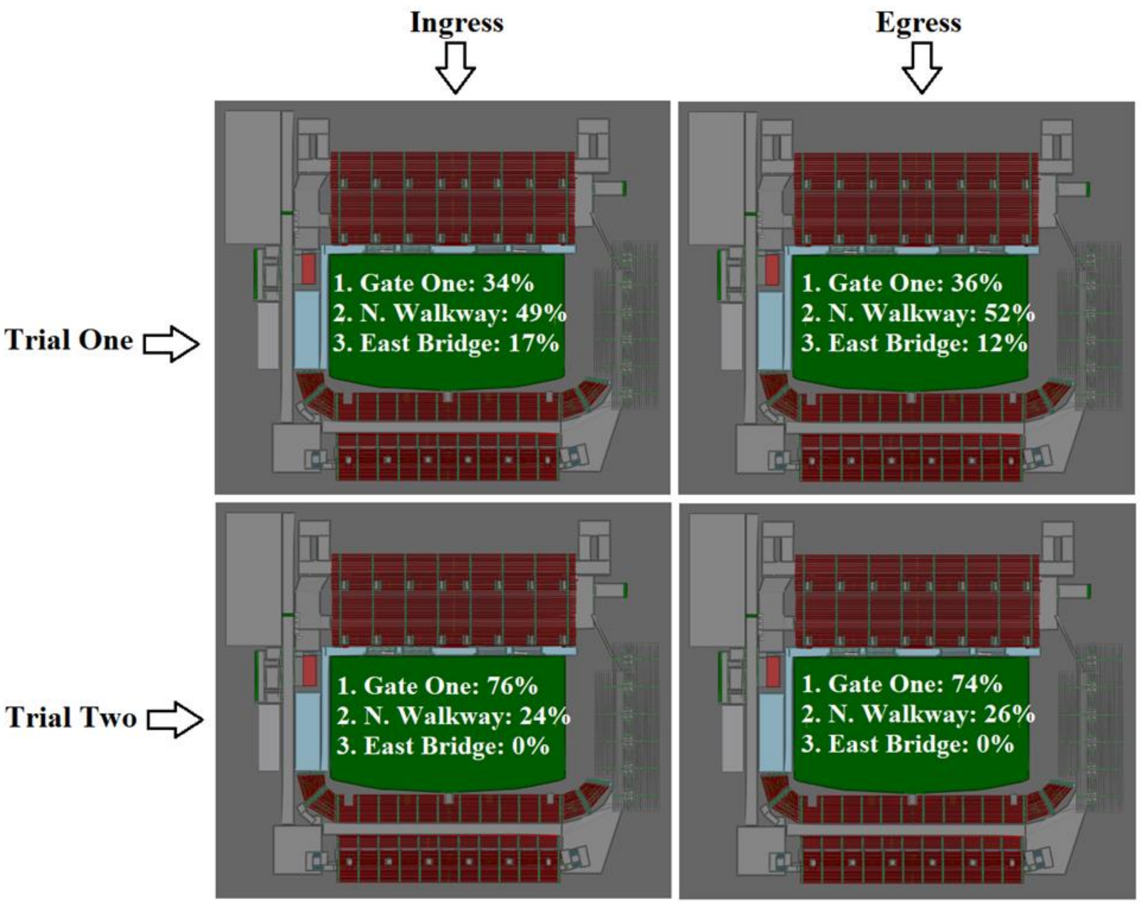

Figure 3.7: Gate Distribution Used for Trials One and Two (Gate 1, North Walkway, East Bridge)

3.6.2 Total Egress Times

Table 3.1 summarizes the attendance numbers and egress times of the two main trials. The 'Egress Time After Game Buzzer" can be defined as the total duration in which people were egressing starting from the end of the game buzzer to when the last person exited the stadium. This differs from the Total Egress Time which also includes the duration in which spectators began to exit the stadium before the end of the game. The criteria used to identify the onset of the Total Egress Time was the point in time in which 100 occupants had left the stadium over a period of three minutes. This measure is arbitrary but was applied to both experimental trials.

Table 3.1: Ingress and Egress Results from Two Trials

Event	**Total Attendance**	**% Capacity Used**	**Total Egress Time**	**Egress Time After Game Buzzer**
Trial One	21,965	92%	45 min 24 sec	17 min 27 sec
Trial Two	23,280	97%	86 min 32 sec	33 min 35 sec

With the closure of the East Bridge in Trial Two, the egress time was extended by 91% compared to that of the first trial. This has major implications in terms of the stadium performance in an evacuation setting if an exit were to be closed, as normal egress performance can be a strong indicator of performance in an evacuation. Inherent risk exists for an emergency situation under these limited gate scenarios as the required safe egress time (RSET) is significantly increased. The exit closure also caused an increase in crowd density when compared to the Trial One event footage.

Approximately one third of spectators that used the filmed exit gates had left before the game's end, a trend which was observed in all trials as depicted in Figure 3.8 and Figure 3.9. Trial One, the researchers attributed this behaviour to the inclement weather, which many spectators appearing to leave the premise prior to the game ending to escape the storm. However, this behaviour seemed to occur independent of all factors such as game importance and score, as Trial Two was one of the final season games. The close game score in Trial Two did result in a large crowd gathered to watch the final minutes of the game on the overhead screen at Gate 1 in attempt to avoid the postgame crowds during egress. This crowd led to an immediate and significant increase in flowrate through the exits upon final game buzzer.

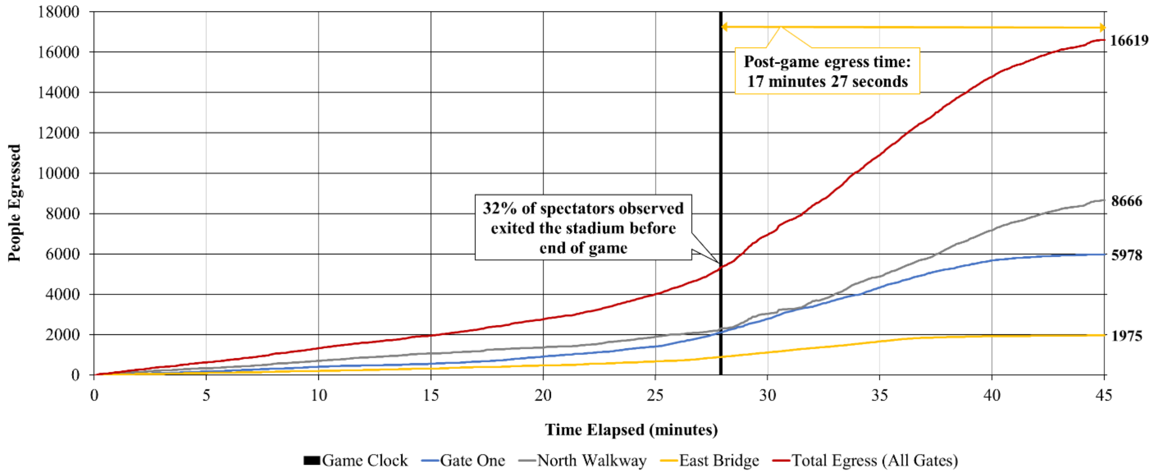

Figure 3.8: Trial One Egress Over Time

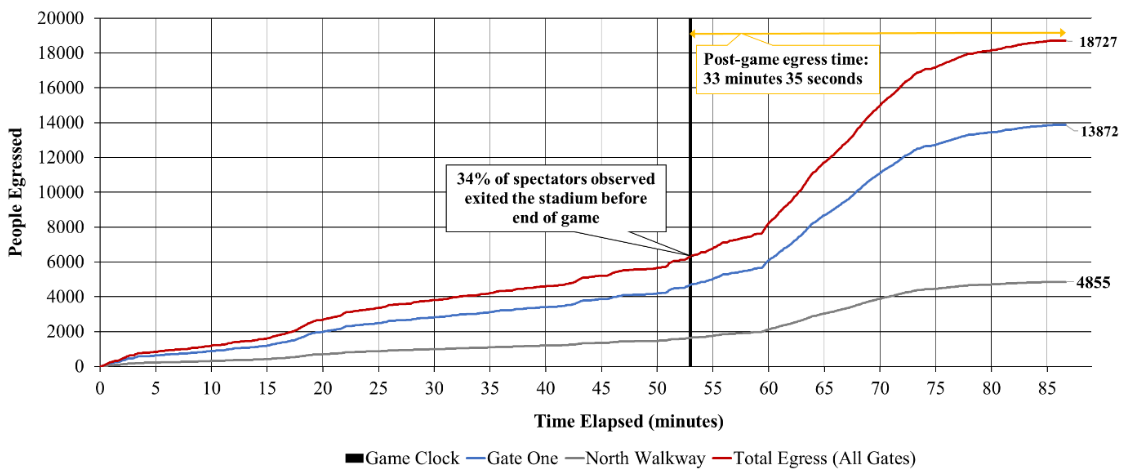

Figure 3.9: Trial Two Egress Over Time

Normalized graphs of the total egress over time for Trial One and Trial Two are presented in Figure 3.10 and Figure 3.11 respectively. These graphs aim to provide a baseline comparison for practitioners to use for stadia egress planning for stadia of similar seating capacity, exit width capacity and of similar architectural configuration. The final egress as a percentage is displayed as a function of the entire stadium capacity of 24,000. Although the stadium attendance levels were over 90% for both trials, the discrepancies between those numbers and the final egress percentage of 69% and 78% presented below can be attributed to several factors: some spectators remained in the stadium for post-game activities, some spectators left prior to the onset of egress filming, and the element of human error exists as counting was done manually.

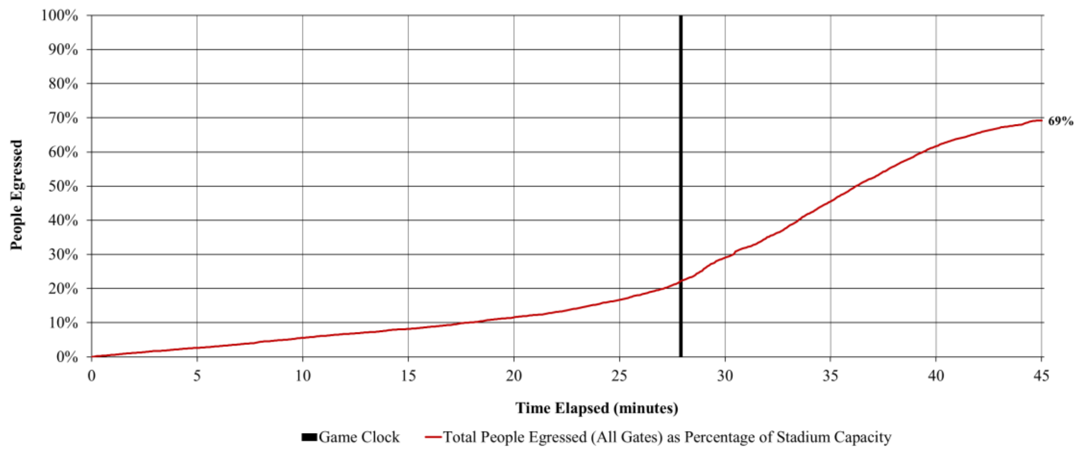

Figure 3.10: Trial One Total Normalized Egress Over Time

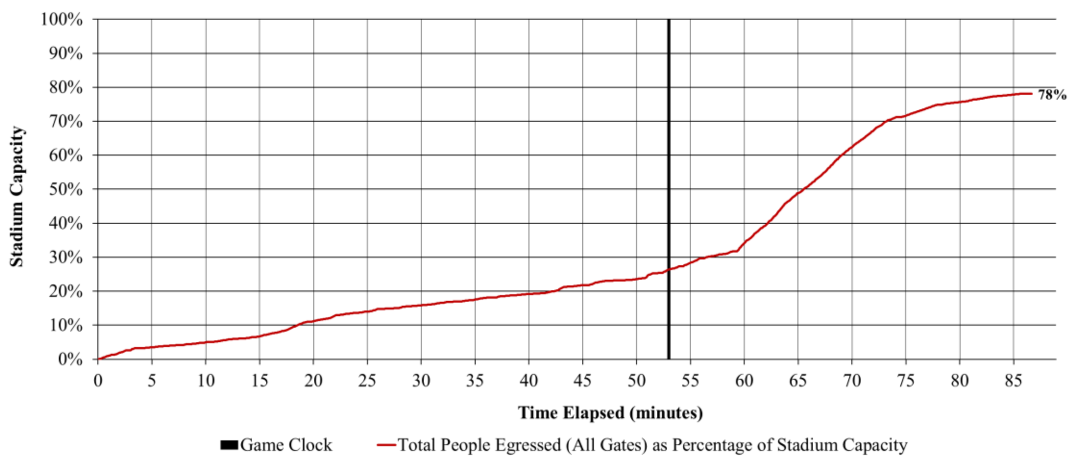

Figure 3.11: Trial Two Total Normalized Egress Over Time

3.6.3 Demographics of Trials

Footage taken by the author's cameras during the events was analyzed and a 20% sample size of the spectators were reviewed to determine the demographics of the events. The age distribution was found to be 6% children, 29% young adults, 53% adults, and 12% elderly. It should be noted that in other sporting events these demographics can vary and should not uniformly be extended to all sports events.

3.6.4 Facial Observations

A Canon EF 70-200 mm (F/2.8L IS II USM) zoom lens was used to observe the crowd behaviour in the denser areas and walkways to search for signs of agitation, frustration, or stress. Due to privacy and to protect the identification of the attendees, these images by the authors decision cannot be shown within the thesis. The term stress can be defined as an individual's somatic response to an event or environment, which may appear in the form of physical or psychological symptoms (Innes, 1984). Physical responses could include facial cues of being concerned, worried, or upset and more noticeable behaviours such as pushing and shoving. In the two experimental trials, observed behaviours did not indicate a significant portion of the crowd was under stress, despite the spectators being subject to crowded areas for longer than eight minutes. Table 3.2 outlines facial cue expression observations tabulated in which around a 20% sample size of each trial was analyzed, and both trials had under 4% of spectators showing a "negative expression" on their face.

Table 3.2: Facial Expression data during Egress

	Trial One	Trial Two
Negative Expression	142 people	76 people
Neutral Expression	1,076 people	1,597 people
Positive Expression	3,175 people	2,983 people

Observed queues were moving and not stationary, and occupants had visibility to the exit and thus the source of any queues that did occur. These sight lines to the exits may have aided in reducing any potential frustration in spectators as any delays would have been known to the pedestrian. However, there are limitations to recognizing stress on film as it could also manifest itself in a less apparent form such as through headaches, anxiety, or depression. A survey would have been most suitable method to uncover these potential underlying measures of stress but was not feasible as ethics clearance by the authors' institution at the time did not clear this action.

3.7 Conclusions

General conclusions are limited to this stadium only. The basis of the design benchmark that states spectators become agitated in crowds after eight minutes originates from the SCICON research. Evidently, the total egress times for the stadium studies carried out by researchers in observed trials and modeling are all well in excess of 8 minutes, amounting to 17 minutes and 27 seconds and 33 minutes and 35 seconds for Trial One and Trial Two respectively. The egress observed was not of a high stress state as most patrons were visibly seen to be laughing and smiling upon queuing and exiting by field cameras. Although this was not an emergency situation, it should be noted that normal egress performance of a stadium is a baseline indicator for egress performance during an evacuation.

Chapter 4: Stadium Model Development, Data Validation, and Applications

4.1 Introduction

This chapter serves to outline the model development of the stadium in which the experimental trials outlined in Chapter 3 were conducted. The model will allow for calibration of input parameters to that of the observed experiments and assess validity of the model. The chapter will conclude by outlining various predictive scenarios that were run in order to assess the effect of demographics on total egress times in this specific architectural configuration. Although these egress observations and simulations were not in the context of an emergency situation, it should be noted that normal egress performance of a stadium is a baseline indicator for egress performance during an evacuation.

4.2 Stadium Model Development

A scale drawing of the stadium was created based on measurements and reference geometry gathered via on-site surveying and from Google Earth Software 2018. The software chosen for initial model development was Google Sketchup (Sketchup) 2018 because geometry built in Sketchup is compatible with and can be imported into MassMotion for simulation analysis. After each component and walkway of the stadium was modelled to scale, every item was tagged with an 'ifc' tag, which is a feature in Google Sketchup that identifies each as a walkway surface, stairs, or ramps. This allowed for easier integration into MassMotion. The final Sketchup model is displayed in Figure 4.1.

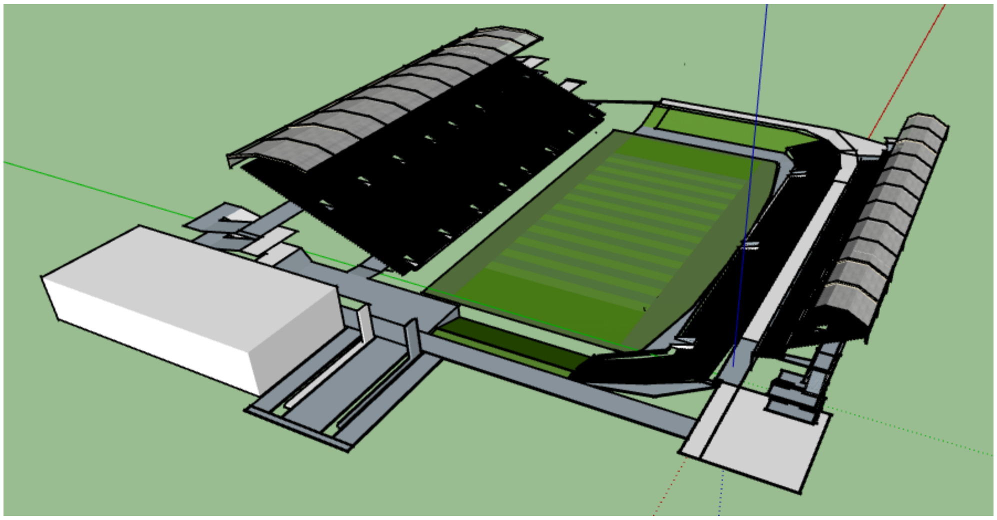

Figure 4.1: Google Sketchup Stadium Architecture Model

This stadium architecture was then imported from Google Sketchup into the MassMotion evacuation modeling software as an ‘ifc’ file. This was done in order to run validation scenarios which were then followed by preliminary predictive egress simulations. The validation runs were calibrated to the experimental trials and the predictive scenarios modeled varying demographic distributions and gate configurations. The final MassMotion model is displayed in Figure 4.2.

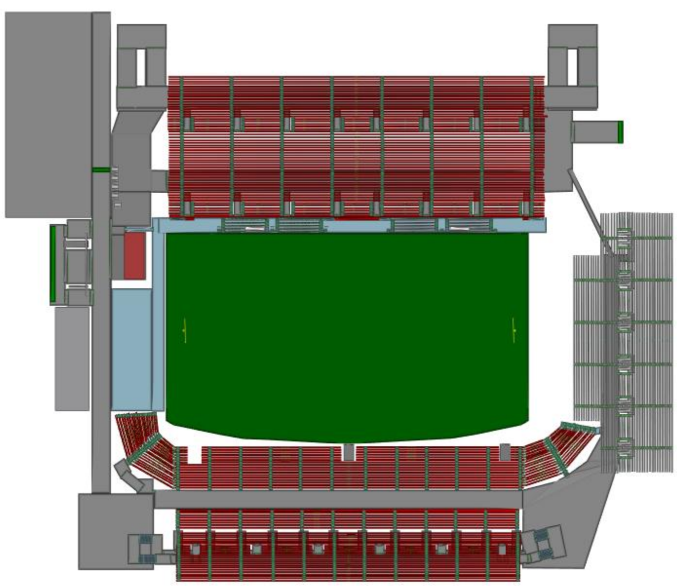

Figure 4.2: MassMotion Stadium Model

4.2.1 Agent Profiles Development

Within MassMotion all agents are assigned a preferred walker speed, representing the maximum speed an agent will walk during a simulation. The agent speeds can move slower then their preferred walking speed due to local crowd density, agent deceleration and the adapted social forces model. The default agent size is 0.5 m in width for all agents. Agents select which route to use during a simulation based on the route they expect to reach their target destination in the shortest time through use of a route cost utility function.

All scenarios were first simulated using the default agent profile for MassMotion, the Fruin Commuter, which is based on the data collected by John Fruin (Fruin, 1971). As aforementioned in Chapter 2, the main limitation with the Fruin profile is that it does not have an available demographic breakdown, but rather applies a nominal distribution of a single walker speed, which is used to randomly assign a speed for all agents. For this reason, the thesis author developed tailored agent profiles to more accurately represent the demographics observed during the stadium trials. Four agent speed profiles were created in order to characterize the behaviour of children, young adults, adults, and elderly. The average walking speeds used were referenced from the findings of studies carried out by K. Ando, which provides a mean and range of speeds for children (<18 years old), young adults (19-36 years old), adults (37-65 years old), and elderly (<65 years old). The minimum and maximum walking speeds used in these ranges were 0.6 to 1.7 meters per second (Ando et al., 1988). For the illustrative purposes of this study, the Ando speeds were applied as they represent a sizable deviation in speed from young to old. The profiles of disabled individuals are not considered, as accessibility in the context of stadia is studied in Chapter 6 by the authors and a profile for disabled patrons will be developed in future work. Footage taken by the author's cameras during the events was analyzed and a 20% sample size of the spectators were reviewed to determine the demographics of the events. The age distribution was found to be 6% children, 29% young adults, 53% adults, and 12% elderly. It should be noted that in other sporting events these demographics can vary and should not uniformly be extended to all sports events. These demographics were used in MassMotion to forecast the events observed in the trials in order to validate the model.

4.2.2 Agent Pre-Movement Times Development

A situation specific set of pre-movement times was defined by reviewing the footage. Of the spectators still seated when the final game buzzer sounded, it was found that people began to exit from the range of five seconds to one minute ten seconds. All premovement times observed are outlined in Table 4.1. Spectators that had no intention of egressing and remained in their seats for postgame activities on premise were not assigned a pre-movement time. These pre-movement times were modeled in MassMotion as a normal distribution. The calculated weighted average of the data set was found to be 36 seconds (based on Table 4.1), which aligns with the behaviour observed in the footage as the majority of people moved around this time frame. The standard deviation of the data calculated and used in MassMotion was 19 seconds.

Table 4.1: Observed Pre-Movement Times

Percent of Spectators that had started Egress	Time (seconds)
Minimum	5
10%	10
30%	17
50%	26
70%	38
90%	57
Maximum	70

4.3 Validation Simulations

As outlined in Table 4.2, two different validation scenarios were simulated using MassMotion. Each simulation was modeled using both default Fruin Commuter speeds as a benchmark and speeds observed from the Ando studies in order to test various demographic distributions for children, young adults, adults, and elderly. Simulation one was calibrated to represent Trial One with all exits open, applied the observed demographic distribution, and populated with the actual number of spectators still seated at the final game buzzer. Simulation two was calibrated to represent Trial Two with the East Bridge closed, applied the observed demographic distribution, and populated with the actual number of spectators still seated at the final game buzzer. Simulation one and two results were compared against the observed trials to validate the model, which was necessary before using the model for further simulation applications.

Table 4.2: Summary of MassMotion Model Validation Simulations

`Simulation Number	Agent Speeds Applied	Demographics	Population Count	Exits Open or Closed
1a	Fruin	n/a	Trial One event actual number of spectators left in stadium at final game buzzer	All open
1b	Ando	As observed at events: 6% children, 29% young adult, 53% adult, 12% elderly	Trial One event actual number of spectators left in stadium at final game buzzer	All open
2a	Fruin	n/a	Trial Two event actual number of spectators left in stadium at final game buzzer	East bridge closed
2b	Ando	As observed at events: 6% children, 29% young adult, 53% adult, 12% elderly	Trial Two event actual number of spectators left in stadium at final game buzzer	East bridge closed

First, qualitative comparison between the simulations and the footage from Trials One and Two was done to ensure alignment in terms of agent density levels and egress route utilization. For example, the author compared the usage of Gate One and the North Walkway in the simulation as illustrated in Figure 4.3 to that of the real stadium in both trials. The three exit points and two points of stadium architecture were verified for their level of congestion and compared to the video footage at three points in time during egress.

Analysis results shown below were simulated allowing the agents to select their preferred exit instead of assigning agents exits based on the collected data. This resulted in a different distribution of gate utilization by agents compared to the experimental trials. Average total egress times did not differentiate between the two exit assignment methods, despite the gate usage varying significantly.

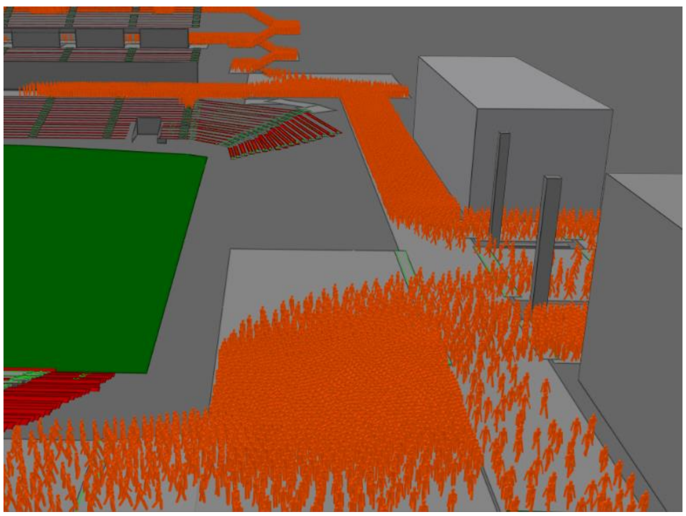

Figure 4.3: MassMotion Simulation During Egress at Gate One and North Walkway

Next, quantitative analysis of the stadium model was carried out Figure 4.4 and Figure 4.5 represent the population count of the model stadium over time for Trial One and Trial Two respectively. Comparing the simulated total post-game egress times to that of the observed trials in Figure 3.8 and Figure 3.9, it can be noted that the model egress times align within 40 seconds for Trial One and four minutes 50 seconds for Trial Two. These times are within reasonable range to consider the model calibration representative of the trials, however it is evident there are other influencing factors at play which account for the degree of variability.

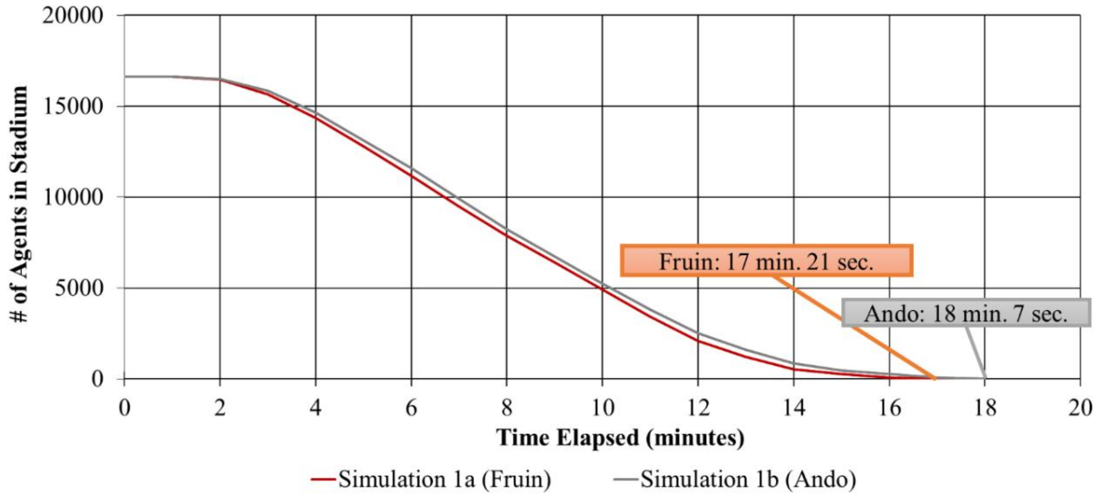

Figure 4.4: Population of Stadium During Trial One Egress (Simulations 1a and 1b)

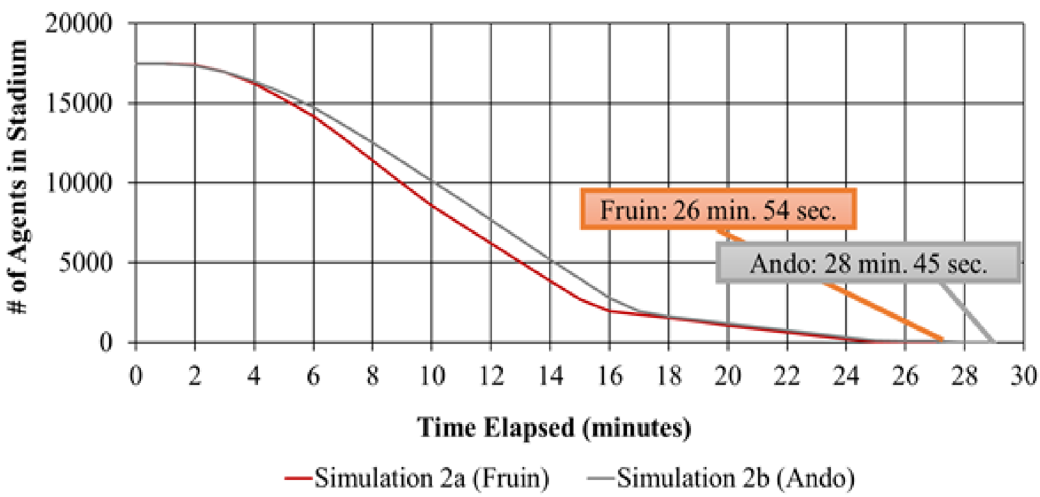

Figure 4.5: Population of Stadium During Trial Two Egress (Simulations 2a and 2b)

One aspect of the sports event that was not captured in the simulation is the concept that people commonly attend sporting events in groups. In general, it is known that walking speeds decrease linearly as group size increases (Moussaïd et al., 2010). Therefore, group behaviour tends to increase overall egress times. Furthermore, the presence of vendors and post-game activities on the field encourages spectators to spend time inside the stadium after the event, making egress not their immediate priority. In contrast, each spectator in the model had evacuating the stadium as their primary task, ultimately reducing the total time required to vacate the grounds.

4.4 Predictive Simulations

After model validation, the simulations summarized in Table 4.3 were run with the objective of testing the egress performance of the stadium at full capacity and the impact of varying demographic distributions in attendance. Simulation three tested the stadium with all exits open at three various demographic distributions: the actual demographics observed at the event, one trial with the majority of spectators as youth, and one trial with the majority of spectators as elderly. Simulation four tested the same three demographic distributions as simulation three, but with the East Bridge closed. The scenario of the increased capacity of 12,000 extra temporary stands has been included in the Appendix A2. This was included as a separate appendix as there was no baseline observed experimental trial to compare it to and it is a preliminary analysis that will be built onto in future work.

Table 4.3: Summary of Predictive MassMotion Scenarios Tested at Fully Capacity

	Simulation Number	Agent Speeds Applied	Demographics	Population Count	Exits Open or Closed
Testing at full capacity	3a	Fruin	n/a	At full capacity	All open
	3b	Ando	As observed at events	At full capacity	All open
	3c	Ando	Higher distribution of young people: 30% children, 45% young adult, 20% adult, 5% elderly	At full capacity	All open
	3d	Ando	Higher distribution of elderly: 5% children, 20% young adult, 30% adult, 45% elderly	At full capacity	All open
Testing impact of one main exit closure at full capacity	4a	Fruin	n/a	At full capacity	East Bridge closed
	4b	Ando	As observed at events	At full capacity	East Bridge closed
	4c	Ando	Higher distribution of young people: 30% children, 45% young adult, 20% adult, 5% elderly	At full capacity	East Bridge closed
	4d	Ando	Higher distribution of elderly: 5% Children, 20% Young Adult, 30% Adult, 45% Elderly	At full Capacity	East Bridge closed

As illustrated in Figure 4.6 and Figure 4.7, the egress times of the stadium model at full capacity require a minimum of 21 minutes 14 seconds, which was exhibited in Scenario 3a. These results suggest evacuation within the eight-minute guidance benchmark could be challenging to achieve in this given anonymous stadium design.

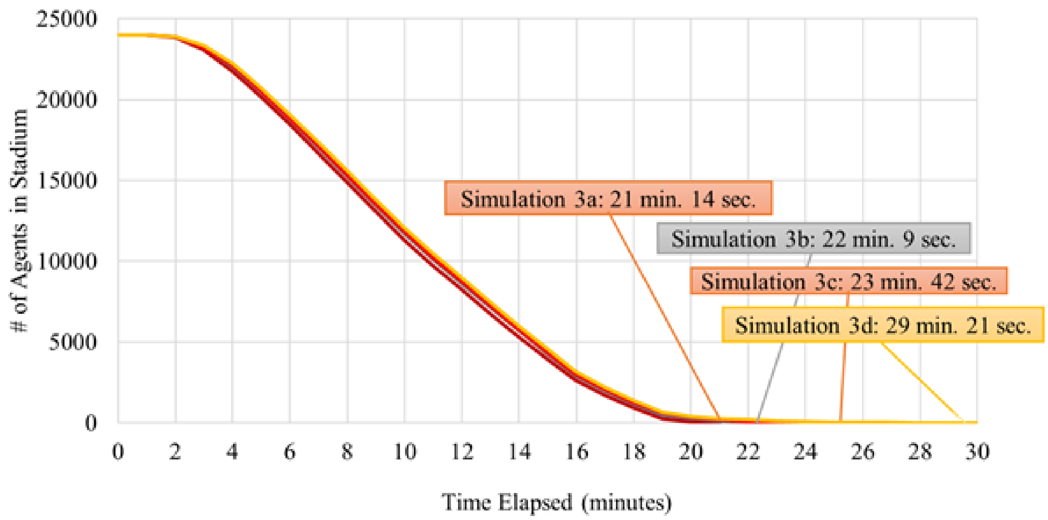

Figure 4.6: Population of Stadium Over Time (Simulations 3a, 3b, 3c, and 3d)

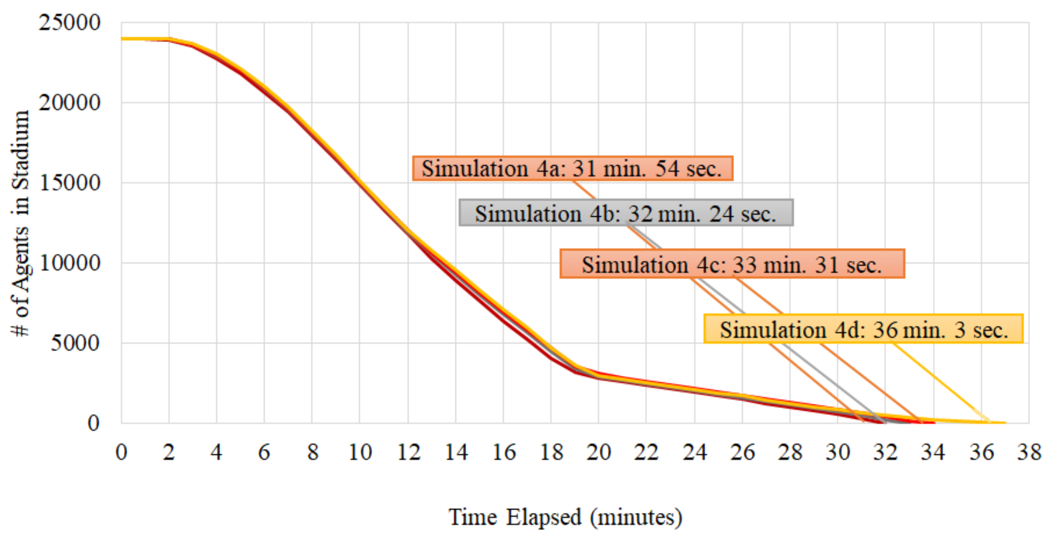

Figure 4.7: Population of Stadium Over Time (Simulations 4a, 4b, 4c, and 4d)

Furthermore, the simulations with a higher composition of elderly (3d, 4d) increased total egress times by a range of four to seven minutes. The simulations with a higher composition of children also experienced total egress times approximately one minute longer than that of the demographics observed at the real trials, which is governed by the children's walking speeds (minimum speed: 0.6 m/s, average speed: 1.1 m/s, maximum speed: 1.6 m/s) that are slightly slower than the average young adult (minimum speed: 1.2 m/s, average speed: 1.45 m/s, maximum speed: 1.7 m/s). When it comes to designing stadia, knowing their intended use including the types of events that will be hosted and what demographics those events may attract are important considerations for egress planning.

All the simulations in this case study were run five times and averaged to find the mean total egress time for the given scenario. These findings showed deviations ranging from one to four minutes for the simulations. The simulations herein indicate that demographics play a role in overall egress times, but congestion is the governing factor for this stadium. In other words, an increase of 10% in the walking speeds of agents in a simulation did not directly translate to an increase of that magnitude in terms of total egress time in the simulation. This was a trend discovered in all simulation runs, concluding that congestion had the largest impact on egress times for this study.

4.5 Conclusions

General conclusions are limited to this stadium only. The basis of the design benchmark that states spectators become agitated in crowds after eight minutes originates from the SCICON research. Subsequent editions of the Green Guide have been issued since 1973, with little update to the context of this guidance. Evidently, the total egress times for the stadium studies carried out by researchers in observed trials and modeling are all well in excess of 8 minutes. The egress observed was not of a high stress state as most patrons were visibly seen to be laughing and smiling upon queuing and exiting by field cameras. To examine stress states accurately though at all stages of egress, it is recommended that a survey approach be employed in a future study in addition to monitoring other metrics. The author's study ethical permissions in this case did not allow to assess these metrics through surveying. Ultimately, a follow on study can work towards the creation of contemporary bench marks to optimize stadium design in this regard. Although this was not an emergency situation, it should be noted that normal egress performance of a stadium is a baseline indicator for egress performance during an evacuation. Modeling various demographic distributions did not govern egress times for this stadium. In other words, an increase in walking speeds did not result in a proportional decrease in egress times, indicating that the service capacity at each exit was the governing factor for this stadium. Future research will be built on the findings of the work and aim to help practitioners establish contemporary design guidance for stadium egress. Additionally, outside influences that may impact the ability to exit will be assessed in future work. For example, Gate One of the stadium leads out to a main road, therefore impediment of this road may hinder ability to egress. Ultimately, the modeling techniques developed will lead to a baseline performance which can be considered for fire safety.

Chapter 5: Stadium Fire Case Study

5.1 Introduction

With growing concerns of public safety in infrastructure where large crowds gather, this chapter aims to characterize human behaviour from a small real stadium fire evacuation and outline relevant considerations for subsequent modeling of this behaviour for emergency planning. This research represents the second phase of the authors' stadium studies following the first stadium study where egress under normal conditions was monitored and characterized to provide background information for subsequent modelling development. The stadium of focus herein had been characterized by the authors under normal conditions before. This chapter assesses spectators in a localized fire caused by unruly spectators at that stadium and characterizes their reactions to the incident in addition to their response to staff cues. The data observed in the footage was applied to tailor a preliminary evacuation scenario using Massmotion of the localized stands to show the associated challenges with representing these actions and their potential impacts on egress.

Stadia have been subject to acts of terrorism related, mischief, and accidental fires for decades and they still remain susceptible despite advancements in security technologies. In 2010, the Chinnaswamy Stadium in Bangalore, India had an incident where two bombs exploded, one by a wall just beside one of the stadium entrances and another several hundred years away on the exerts of the stadium. Although the bombs were of low-intensity, at least 8 people were severely injured (Berry, 2010). Furthermore, in 2017, a bombing at a stadium in Manchester resulted in mass egress during a concert. The incident had 22 casualties and over 100 injuries (Lizzie, 2018). Evidently, these events were planned and caused by people with preconceived notions to cause harm. In other events, it has been documented that mischief, vandalism or accidents have provoked localized or full evacuations of stadia in emergencies. All of these events show how not only security protocols are vital to maintain stadium safety, but also evacuation planning with respect to the uncertainty with the behavioural uncertainty in a dangerous situation. With advancements in artificial intelligence and high performance computation, evacuation modelling is currently evolving to fully consider a range of realistic cognitive actions.

5.2 Behavioural Study

Due to the ethics involved with the authors running their own emergency evacuation drills in stadia, this study is limited to footage of a sole case fire incident in the stadium. Understanding potential behaviours aids in assessing the fire vulnerability of stadia when the modeling inputs and parameters are tailored and justified. The authors' model represents a localized area, however the findings could be extrapolated to more highly populated scenarios to prompt additional risk-based framework development for which the authors are currently investigating in future work. The following case study was assessed considering the information each occupant had in the incident and each individual's associated behaviours. At the beginning of the seven films of footage, the effective occupancy of the local area was 20% of the capacity of the localized area (N=32). It is estimated that the localized area maintained an original 80% of capacity prior to the fire event (N=128) resulting in a controlled evacuation of 100 prior to filming. The adjacent stand was considered to be at full capacity. There were no spectators located in the stands north of the considered area. The section of seats where the fire occured are typically sold to encourage spectators who support the visiting team to sit together. The author acknowledges that this study is limited to the publicly available footage obtained and therefore there is a gap in the premovement observations of all spectators. The reported quantifications herein are noted as estimations because smoke and camera quality impairs the visibility in the footage available to the authors. The location of the fire origin relative to the entire stadium is illustrated in Figure 5.1. The authors did not investigate the fire spread dynamics. The focus of the behavioural study was on the localized area, as clear footage for the adjacent stands was not publicly available either. However, the adjacent stands will be considered in modeling to assess potential crossflow effects at the stairway shared between the two sections.

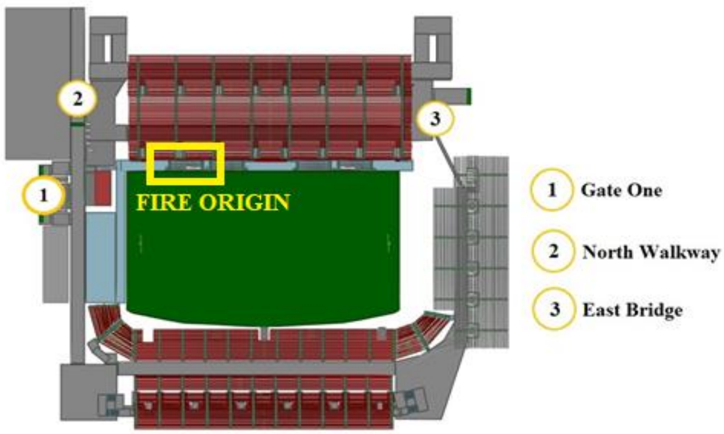

Figure 5.1: Stadium Architecture and Relative Fire Origin

A timeline and key events of the case study are provided in Table 5.1. This timeline is a compilation of seven different video clips from various perspectives of the stands. The footage obtained was gathered from publicly available videos. The total footage length amounted to 6:20 minutes and video clips varied in length from 0:14 to 1:53 minutes. The video portions were time-matched based on key events in the footage by the authors to create a global timeline of the fire and resulting behaviours. The stadium itself did not have footage of the initial phases of the event available and the authors were not present at the time of the incident to film. The earliest start of the video compiled is defined as “time zero” in the timeline below. Investigation of the timeline prior to this point would require additional study and may require lots of personal interviews with attendees present at the fire due to the lack of footage. However, it is known that the incident occurred during the second half of the match and the “masked individuals” were fans supporting the opposing team. In terms of score, the opposing team was winning by one point when the fire occurred.

Table 5.1: Global Timeline of Incident where Time Zero is when Records Begin

Time	Description
0:00	Dark smoke emanating from north stands.
0:04	Fire becomes visible. One masked-spectator beside the fire lights a smaller flare.
0:06	Fire is significantly visible.
0:15	Flare thrown onto field.
0:28	Staff seen removing flare from field. Masked-spectators seen dancing on seats while holding on to back railing.
0:35	Explosion in stands seen and audible.
0:36	Some unmasked-spectators in north stands begin to egress away from fire origin. One man is observed running towards east stairs (See Figure 5.5 for location of stairs).
0:45	Audience member states "this is no longer fun".
0:50	Several unmasked-spectators seen gathering their bags and starting to egress through west stairs (See Figure 5.5 for location of stairs).
0:51	Some unmasked-spectators attempt to descend via east stairs which is obstructed by person holding white flag.
0:59	Flames seen in front of banner in rows 1-2. Banner is exposed to flames.
1:02	Banner catches fire.
1:04	Remaining fans in row 5 egress to west stairwell. One spectator removes flare from under banner.
1:08	Masked-spectator tears banner and flames travel-up sides. People dwell at stairwells to film.
1:11	Security begins extinguishing the flags with a handheld extinguisher.
1:22	Fire is out. Masked-spectators holding a large flag turns around to look at remains.
1:35	Four masked-spectators still seen dancing on top of seats. Two others wearing black shirts and hats also are on top of the seats while pointing and dancing with the masked-spectators.
1:47	Authority figures tell masked-spectators to stop dancing on seats and directs them to leave.
1:48	Masked-spectators carrying flag starts to egress towards west stairwell and masked participants follow.
1:50	Staff members directs an unmasked spectator filming with their mobile phone to egress.
1:52	Venue volunteer lifts lid on trashcan containing another flare, which releases a small explosion.
2:07	Masked-flagbearer and participants make way through small crowd at west exit.
2:40	In audio background, a spectator yells "everybody panic".
2:55	Localized stand clear.

5.2.1 Masked Individuals

We define a sub-group of an estimated seven people as the "masked spectators", which represent the group that launched the flares in the stadium. This group was identified on the virtue that they obscured their faces with a cloth mask near the fire origin and had associated significant delay in egress. The behaviours observed in the footage will be outlined relative to various groups and demographics that were seen carrying out behavioural actions. It can be hypothesized that since the individuals that launched the flares were all wearing masks, their harmful intentions may have been pre-planned. In terms of the masked individuals, inaction was their primary response as evidenced by how none of them attempted egress while the flames were present. As displayed in Figure 5.2, the masked individuals were observed dancing and chanting on top of seats (starting at 0:28) even when the situational risk had grown to the point where there was potential danger for the fire to spread further. It is likely the situation had escalated past their expected intentions and the individuals exhibit normalcy bias.

Figure 5.2: Masked Individuals seen dancing on top of seats

Normalcy bias is the phenomenon that people disregard the threat of a situation and disbelief that anything occurring will put them at risk (Drabek, 1986). The notion of conformity manifests itself in the masked individuals as each person conformed to the stay-put behaviours of their group since no staff member was immediately present to direct egress until well-after the flames had been extinguished.

5.2.2 Non-Masked Individuals

Delayed pre-evacuation was observed as non-masked spectators were either celebrating near the fire or photographing the incident using their mobile phones. Evacuation can be viewed as a social process, as there was a distinct difference in egress time and decisions between the masked individuals, spectators in the stand who chose to stop and film the situation, as seen in Figure 5.3, and others who decided to omit from the area immediately.

Figure 5.3: Individual Filming the Crowd

It was apparent in the footage that at least five people in the localized stands filmed the incident the entire duration until the fire was extinguished, this number represents 16% of the non-masked spectators observed on the video recordings. As these idle filming individuals blocked egress out from those isles and the fire origin blocked egress in the opposite direction, non-masked spectators were observed climbing over the edge of seats to reach one isle lower in order to exit as observed in Figure 5.4. Aside from those choosing to film the incident, other delays in pre-movement times were a result of acts of appropriation where spectators prioritized gathering their belongings.

Figure 5.4: Individual Climbing Over Chair

Many groups, including the masked individuals and also the non-masked spectators, did not attempt to egress until directed by staff despite being immersed in a scenario with inherent risk. This observation of inaction emphasizes the importance of ensuring staff give direct cues in an emergency in order to reduce pre-evacuation time and prompt egress. Qualitative analysis of the behaviours in this case study affirm many behavioural concepts which have been witnessed by human behaviour researchers in the past but also reveals behaviours which would have not been commonly predicted based on past research. Table 5.2 outlines frequency of selected observed behaviours.

Table 5.2: Frequency of Selected Observed Behaviours

Frequency	**% of Spectators at Time Zero (of Table 1)**	**Behaviour**
9	28%	Non-masked spectator egressing immediately from area
7	21%	Masked individuals making up group that launched flares
6	19%	Spectators in localized area evidently consuming alcohol
5	16%	Non-masked spectator filming using mobile phones
5	16%	Non-masked spectator not egressing, conforming to group of those filming
32	100%	

5.3 Model Development and Set-Up

The localized stand area consists of five rows, seating 124 occupants. Row one is denoted as the bottom row in Figure 5.5 and row five is denoted as the top row in the figure. The reason rows one and two have less seats than rows three through five, or the white space in Figure 5.5, is because that space is designated for people with mobility aids and physical disabilities (none of which were recorded in the video recordings). The seats are numbered individually starting at number one per row on the right side of Figure 5.5. There were two available stairwells for the people the localized stand area to egress to, the west stairs on the left side and the east stairs on the right side of Figure 5.5. Note that although these stairs were not an exit from the entire stadium, these were considered the “exit” for the simulation, in which the individual was considered clear from the fire zone. The stands adjacent to the fire stands were also modelled in order to assess the effects of crossflow into the east exit, which was shared between stand sections. The adjacent stands seated a higher capacity at 154 seats, as there is no space for people with mobility aids in this section.

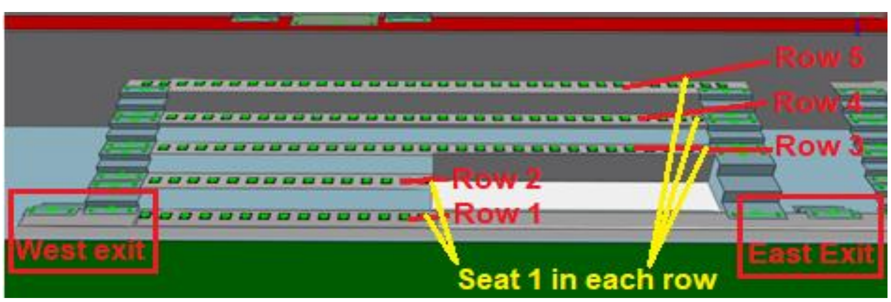

Figure 5.5: Naming Orientation of Localized Stand Area

The MassMotion Fruin Commuter Profile was used as the agent profile in all models. The default value for the agent body radius is 0.25 m. This profile applied a nominal distribution of walking speeds, with an average of 1.35 m/s, a minimum of 0.65 m/s, and a maximum of 2.05 m/s. The standard deviation applied was 0.25. Demographics of the localized stand area was observed to be of a compromised of young adults ranging in age from 19-36 years old, which was estimated based on visual analysis of the footage. The average walking speed of the default profile is in alignment with average walking speeds for this age range by frequently referenced documentation (Ando et al., 1988).

Two hundred and seventy-eight journey functions were programmed, each corresponding to one agent and one seat in the stands. A journey function is a function in MassMotion that allows an agent to be assigned to move from one location to another with a series of tasks in between, such as waiting, stalling, or moving to a certain area before choosing their exit based on a lowest cost function. This was done to allow simple evacuations, but also to allow the individual's journey to be tailored in future research by the authors. An example of a programmed journey function includes designating spawning of one agent from a specific seat portal, such as Row 1 Seat 1. The set assigned goal destinations were then designated on a lowest cost basis, with the option of both the west and east exit as seen in Figure 5.5. The agents are programmed on a lowest cost basis in terms of exit selection. The start of the simulation was assumed to be the time of recognition of the fire by occupants in the area. It is important to note that our simulations assume time zero to begin at fire recognition, this is not exactly the same time as when video recordings were made. A like for like time stamp observation therefore has significant limitation in discussion. People climbing over the seats was not considered in modelling.

5.4 Results and Discussion

The base model of the localized stands was populated with 124 occupants, to model the egress of the area at full capacity with no model tailoring. The adjacent stands were not modelled in this first scenario. Figure 5.6 shows the localized area five seconds into the simulation. It can be observed that about 25% of the stands choose to use the east exit and the remaining choose to use the west exit. Before running the model at a lower capacity and with more tailored parameters, the localized stand area and the adjacent stand area picture in Figure 5.7 were simulated in unison to see if the effects of crossflow at the east exit needed to be considered.

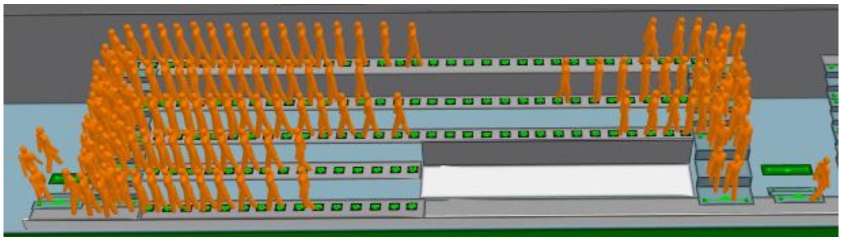

Figure 5.6: Localized Stand Area Five Seconds into Scenario (No Crossflow Considered)

Figure 5.7: Localized Stand Area Five Seconds into Scenario (Cross Flow Considered)

As seen in Figure 5.8, a time-lapse of agents evacuating over time shows an average total evacuation time of 1:21. This value was obtained with convergence over fifteen runs. Between all fifteen iterations, this value ranged from 1:18 to 1:24, proving convergence of total evacuation time. The scenario run with crossflow into the east exit leads to nearly identical results (average total evacuation time of 1:22) to the prior scenario with no crossflow in the stairwell modelled. This implies that crossflow from the adjacent stands will not be influential over egress times of localized stand area, and that the east exit was designed wide enough to provide crowd flow capacity to both stand sections.

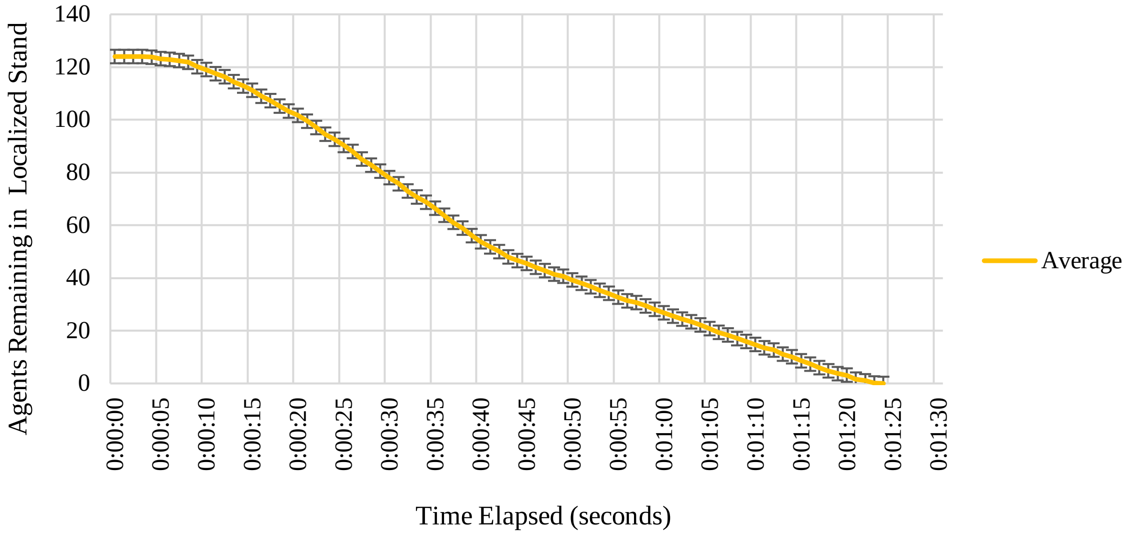

Figure 5.8: People Evacuating from Localized Stadium Stands vs. Time (No-crossflow)

As would be expected, this model overall evacuation time was evidently less than that of the real fire incident as per the dominating behaviour of masked spectators (2:55). Limitations to this method include only considering one parameter or point in time, as opposed to considering the population count at all points in the simulation. Contrary to the aforementioned results in Chapter 4, where exit capacity governed egress times under normal egress conditions for this stadium when tested at full occupancy of 24000 agents, the total evacuation times in this study are controlled by behavioural acts on a localized level. Chapter 4's results illustrated reasonable alignment quantitively (egress times) and qualitatively (behaviours) between experimental footage and modeling with little informed tailoring needed. However, this study shows that tailoring may be more pertinent to modeling evacuation behaviour under emergency conditions, as there is greater underlying uncertainty when it comes to modeling these behaviours.

To assess the impact of the 16% of the individuals who turned to film the event as earlier mentioned in Table 5.2, the model used the data observed from the study and extrapolated it to a full capacity model (where we assume 5x those who stayed to film as a highly conservative approximation. This represented a total of 25 individuals out of the 124 occupants. Twenty-five of these filming individuals were placed evenly spaced in each rows one through five. It was hypothesized that these filming individuals would remain preoccupied until a staff member arrived and gave them a cue to exit. The time for this authoritative figure to provide this cue was set to 1 minute 50 seconds as exhibited in the case study (again caution being made that this time stamp is at the beginning of filming and may indeed be higher in value). Modeling the impacts of these behaviours come with several challenges. For example, two filming individuals located at Row 4 Seat 22 and Row 4 Seat 27 as pictured in Figure 5.9 were constrained occupants in Row 4 Seats 23 through Seat 26 to their seat until their cue was received at 1 minute 50 seconds. Simulations were run fifteen times to based on the same convergence requirements as aforementioned for the previous simulation. Comparing this to the footage, it was known spectators were observed climbing over seats in front of them into the isle below in order to leave. This method would only allow agents not constrained between filming individuals to move and egress freely.

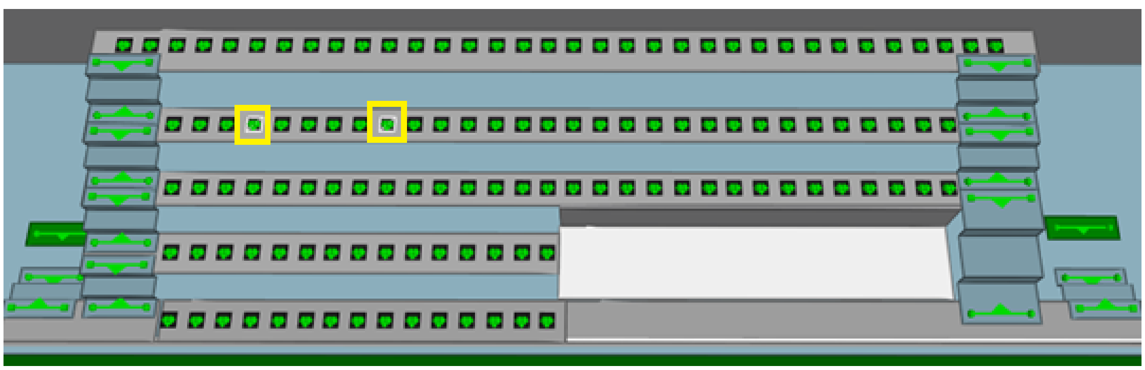

Figure 5.9: Row 4 Seats 22 and 27

Additionally, a filming individual modelled in a seat such as Row 3 Seat 15 would re-route agents who would have initially been route towards the west exit on a lowest cost basis, but then would be re-routed to the east stairwell due to the isle blockage. This does not consider that this agent would then be passing through the location of emanating smoke as it is near the fire origin. Considerations and accommodations to be able to incorporate such behaviours such as those filming need to be made to still foster a scenario that allow those not filming to move as they would in a localized fire. For example, a slight widening of the isle way would allow agents to pass the idling individual, but still impede movement to the egressing agent relative to if the filming individual was not there.

5.5 Conclusions

Key findings from this study include that behavioural acts are more likely to dominate egress times on a local area than architecture. It was found that 16% of individuals in the observed footage stopped to film the fire incident instead of egressing. Furthermore, the masked individuals did not attempt to leave until they were directly prompted by staff, despite visible flames in close proximity to each of them. Modelling efforts showed that model calibration and consideration of observed behaviours such as those filming with their phones are pertinent in emergency situations to reflect and predict realistic evacuation times under emergency conditions. Evidently, there is greater underlying uncertainty when it comes to modeling these behaviours in evacuations as opposed to large-scale egress models under normal conditions where architecture may govern egress times.

Limitations include that culturally these egress procedures may not all be transferrable. For example, stadium evacuation procedures in some countries would not typically specify the pitch for egress since the field is considered 'sacred' and unlikely to be used without heavy prompting by authoritative staff. Furthermore, it is unknown exactly how many spectators were in the stands prior to the start of "time zero". The study was limited by the publicly available footage the authors were able to obtain.

This study indicates further work is needed regarding more observations of emergency case studies would allow researchers to create a database in which behavioural trends in emergency situations could be tabulated. For example, a compilation of situations similar to this case would allow for a database of people choosing to stop for a certain amount of time to film the fire as opposed to beginning to evacuate immediately. This would require a lot of case studies and a statistically significant amount of people carrying out a certain behaviour to be able to apply the findings to a model with confidence. It is considered rare that security footage at a stadium for an emergency egress of a real situation would be released for research purposes, however in doing so the community could more readily improve emergency egress planning.

Culturally these egress procedures may not all be transferrable. For example, stadium evacuation procedures in some countries would not typically specify the pitch for egress since the field is considered 'sacred' and unlikely to be used without heavy prompting by authoritative staff. Qualitative analysis of the behaviours in this case study affirm many behavioural concepts which have been witnessed by human behaviour researchers in the past but also reveals behaviours which would have not been commonly predicted based on past research and experience. This study concludes that tailoring model parameters is even more important to modeling evacuations under emergency conditions where behavioural aspects may govern, as there is greater underlying uncertainty when it comes to modeling these behaviours as opposed to large-scale egress models where architecture may govern egress times. Ultimately, uncertainty associated with predicting and modeling adaptive behaviours can be reduced as this investigation reveals how behaviours can begin to be rationally controlled and considered.

Chapter 6: Stadium Accessibility Considerations

6.1 Introduction

It is known that 10.5% of Canadians aged 15 years and older have a mobility-related disability, which requires special considerations to accessibility while these individuals are in public spaces (ISEDC, 2011). This presence of disabilities is even more prevalent in the senior population at 31.5% of Canadians over the age of 65 (ISEDC, 2011). It is vital infrastructure used for public events, such as sporting games, are inclusive and allow for people with mobility concerns to be able to utilize the space and enjoy the same quality of life compared to those without an impairment. The space needs to be encouraging for those with mobility impairments otherwise a non-accessibility friendly stadium will be a deterrent for those to attend events. To ensure such public venues, such as stadia, are accessible and safe for the entirety of the public it is necessary to be able to model crowd flow within the architecture with consideration to those with disabilities. This process requires attention to widths of walkways to ensure capacity for those with mobility aids, placements of stairs, availability of elevators, availability of accessible seating, and also the ability to model the movement of these individuals within the structure. With limited data available on the number of disabled individuals attending events hosted at stadia and the characteristics of these individuals, the need exists for further studies in the field. The goal of this experiment was to conduct extensive data collection on those with accessibility requirements during events at stadia. The scope of developing a full applicable modeling profile for each of these individuals is very intensive and outside the scope of this thesis. This chapter aims to provide a first-stage for starting the development of these profiles, including extensive data collection on disabled individuals in stadia and a starting benchmark process for walking speed development.

6.2 Experimental Methodology

6.2.1 Experimental Overview

Filming trials were carried out at a Canadian stadium during an international sporting event spanning seven days. Of these seven days, three full days were selected for crowd filming including one preliminary round day (called Day 1), the quarter finals (called Day 2), and the day of the finals (called Day 3). This strategy was chosen in order to observe varying attendance numbers, as the finals day drew a larger number of crowds than the preliminary round. Each day consisted of a morning set of matches and an evening set where spectators required a separate ticket for each session. This required all spectators to egress from the stadium bowl mid-day, and had to re-enter about an hour later when the stadium bowl re-opened for the evening games. During this time, spectators were allowed to remain in the surrounding stadium facilities to enjoy the activities and vendors. The event had a recorded attendance of 150,597 attendees over the 7 days and 13 different games spanning these days. Weather conditions for the first, second, and third day averaged 28, 25, and 27˚C respectively. All days were sunny throughout the day, with the exception of day one which was subject to 6 mm of rainfall over the course of an hour in the evening.

6.2.2 Stadium Architecture

The stadium of interest was constructed in 2004 and was 14 years old at the time the filming trials herein were conducted. The stadium has a capacity of 12,500 people, with an additional 4,000 of temporary bleacher stands that were erected on the top deck of the stadium, providing a total maximum capacity of 16,500. A map of the stadium is included in Appendix A3, which is also marked with the filming set-up that will be described further in Section 6.2.3. The stadium bowl is located alongside a series of pathways winding through a “pedestrian village” which provides space for food and sporting vendors and activities for spectators to spend time at. This pedestrian village area was subject to an inflow and outflow of people throughout the day. This crowd flow was heaviest during the time between the morning and evening games, in which spectators were not permitted to stay in the stadium bowl during this timeframe.

6.2.3 Filming Equipment and Set-Up

The first camera used was a Go Pro Hero 6 and was placed in camera position #1 capturing the main entrance queue. The point of view for this camera can be seen in Figure 6.1. The camera placed in position #2 was a Canon EOS 5DS (50.6 megapixels) which captured ingress and egress in the pedestrian village. The perspective on the pedestrian village captured is displayed in Figure 6.2. Another Go Pro Hero 6 was placed in position #3 to capture the stadium bowl stands with a view as shown in Figure 6.3. Lastly, a Canon EOS 5D Mark III (22.3 megapixels), marked by position #4, was primarily used to capture various angles of the stadium bowl in Figure 6.4, which included close-ups of the stadium bowl entrance and exit points and isles.

Each of the high resolution cameras sported a 24-105mm lens and were mounted on compatible, high quality tripods. The sports cameras were mounted on a GoPro Jaws: Flex Clamp Camera Mount. Two spare batteries for each camera and Go Pro were brought to site in order to ensure enough power was available for the entire filming duration. One charger for each camera was brought to site in order to charge batteries when required.

Figure 6.1: Main Entrance (Go Pro Hero 6)


Figure 6.2: Pedestrian Village (Canon EOS 5DS)

Figure 6.3: Stadium Bowl (Go Pro Hero 6)

Figure 6.4: Bowl with Focus on Entrance Points (Canon EOS 5D Mark III)

6.2.4 Filming Logistics

Each day the filming points were set-up prior to the main gates opening for ingress. The times the gates opened in the morning varied between 10 am and 11 am. Researchers began filming upon gate opening and continued to film until all morning matches were complete, typically around 3 pm to 4 pm. As aforementioned, when the morning games were over, a complete egress of the stadium bowl in Figure 6.3 was mandated, and the majority of spectators proceeded to exit the premise or spend time in the pedestrian village prior to re-entering for the evening matches around 6 pm. Those with only an evening ticket and no morning ticket were not permitted to enter the stadium grounds until one hour prior to the first evening match. This schedule was applicable to the weekday games which the first two filming days took place over. The third date of filming was on a weekend and the game ended around 7:30 pm, in which an entire egress of the stadium was captured, as well as the clearing out of most of the premise. Most spectators chose to leave immediately instead of spending more time at the vendors in the village. The egress of the stadium bowl took approximately 15 minutes from the end of the game to the last individual that exited. A summary of the matches filmed, their respective attendance levels, and any notable factors can be found in Table 6.1 where many are beyond the scope of the current thesis to analyze.

Table 6.1: Summary of Matches Filmed

Filming Event	% of Stadium Bowl Filled	Notable Factors
Day 1 – Daytime Match	40%	Large bags with free stuff being handed out
Day 1 – Evening Match	75%	Significant downpour of rain
Day 2 – Daytime Match	30%	n/a
Day 2 – Evening Match	80%	n/a
Day 3 – Afternoon Match	92%	n/a

6.2.5 Challenges and Limitations

Notable challenges from this phase of experimentation include equipment defects with the Go Pro 6 batteries. As seen in Figure 6.5, the battery consists of a tab connected to it, boxed in yellow, which is intended for use of removing the battery out of the device. This tab pulled out from the battery due to a common product defect acknowledged by Go Pro (GoPro, 2018). This is caused due to the adhesive between the tab the device weakening with time and this process can be accelerated when the device is exposed to heat for long periods of time, such as filming in the sun.

Figure 6.5: Go Pro Battery Set-up

Since the battery tabs became detached, the researchers instead removed the batteries with “tweezers”, in which they inserted them into the gap the tab used to be and lifted the battery out. This caused wear and tear in terms of the aesthetics of the top of the batteries, however it did not affect their functionality.

6.3 Experimental Data Analysis

Of a total of 102 hours of footage collected, 49 hours of footage were selected to be analyzed for this thesis on the subject of accessibility, with focus being on 28.5 hours of footage from the pedestrian village and 20.5 footage from the front gate. The number of hours required for analysis of the 49 hours of footage was approximately 150 hours, which included creation of the database template of Microsoft Excel 2016, going through the footage, and recording the data in the data template. The stadium bowl footage still remains for future analysis, as this was limited by the project scope [4]. Footage was analyzed visually and data was tabulated using Microsoft Excel 2016 based on a standard amount of categories. The data tabulated included people that had specific accessibility or mobility considerations and were organized based on the following categories: rollator, walker, walking stick, cane, manual wheelchair, electric wheelchair, mobility scooter, person with a roller suitcase, person with an oversized bag, families with young children, person needing assistance by another individual, and seeing-eye dogs. A more detailed description of what each of these categories covered can be found in Appendix A4. Further information was gathered for each instance of the accessibility points above tabulated. For each data point, it was recorded how long the individual or group was on screen for, through which path they entered and exited the footage from, their gender, and approximate age.

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[4] For this phase of experiments, it was not a priority to test the stadium for egress, but rather gather a database of people that have accessibility considerations. However, the egress footage obtained can be used in future work to assess whether the conclusions from Chapter 3 hold true in a different stadium.

6.4 Experimental Results

The data collected was tabulated separately based on footage at the front gate and footage at the pedestrian village. Of all footage analyzed, there were 3,238 cases of individuals with accessibility needs observed. It is important to note that because the cameras were rolling simultaneously these data points could represent the same individual more than once, as people were captured walking through the main gate and then many of these would have passed through the pedestrian village afterwards. The purpose of gathering the maximum amount of screen time for these individuals, even if they are double counted, is to provide an adequate amount of data to allow for development of agent profiles for simulated models for each of these accessibility concerns. The process for this model and resource requirements for this profile development will be further outlined in Section 6.4.1 of this chapter.

As seen in Figure 6.6, family with young children represented the highest amount of data points collected at 362 cases for those passing through the front gate, followed by 86 cases of manual wheelchair users. Evidently, the pedestrian village footage exhibited a higher number of total accessibility cases as displayed in Figure 6.7 because of the nature of people circulating around the pedestrian village, with potential for people to pass through the camera point of view more than once. It should be noted that the majority of the “Other” category consisted of people pushing large trash bins and people pushing a stroller.

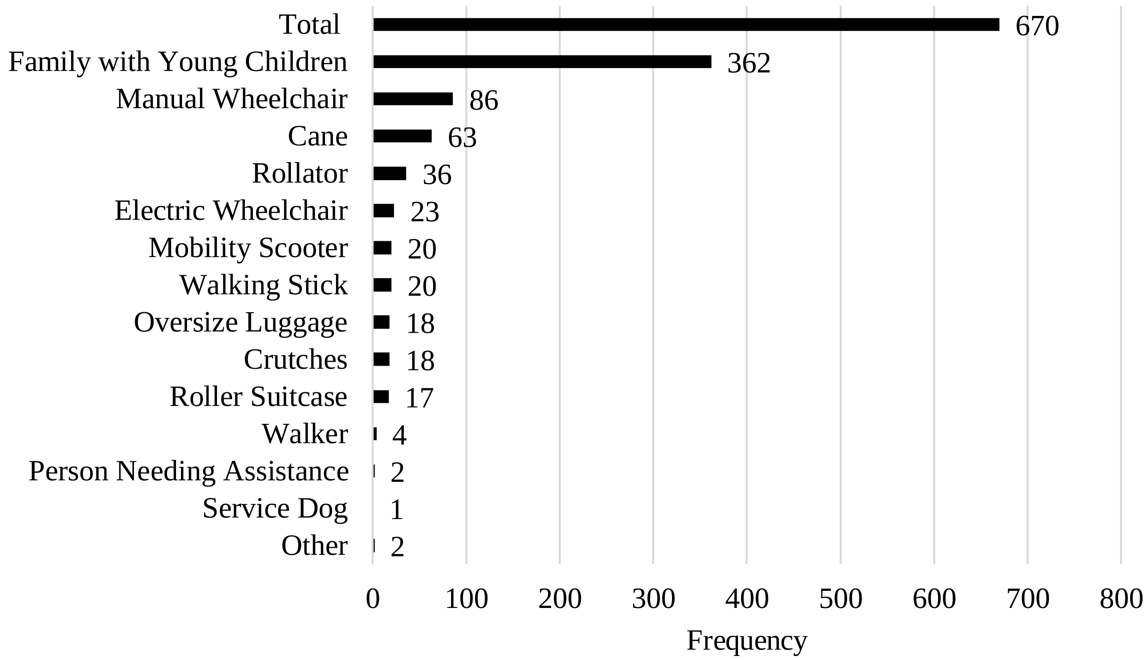

Figure 6.6: Stadium Mobility Consideration Cases Count at Front Gate

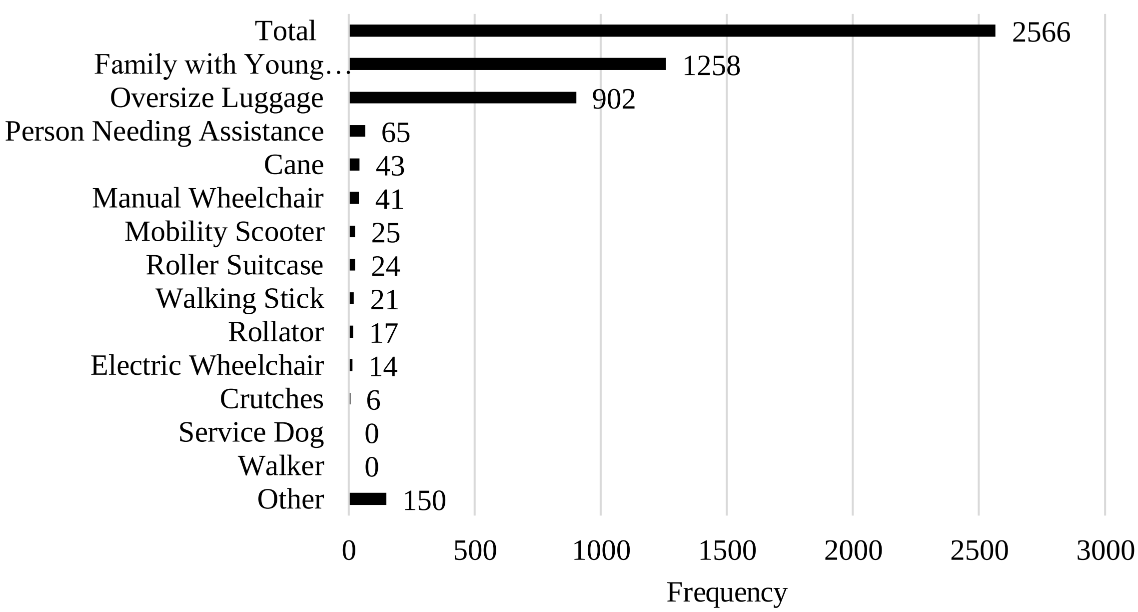

Figure 6.7: Stadium Mobility Consideration Cases Count at Pedestrian Village

Next, it was determined what percentage of the total stadium attendance each accessibility category represented. The total event attendance was obtained from the stadium manager to be

150, 597 over the course of the 7-day event. Each day of the event did not capture an equal share of this attendance, due to the first few days hosting preliminary rounds and the last couple days hosting semi-finals and finals which drew a larger crowds. In order to determine the attendance for each day, an estimate of the crowd captured per day was made and outlined in Table 6.2.

Table 6.2: Estimated Captured Attendance per Day

	Assumption of % Captured	**Total Daily Attendance**
Total 7 Day Attendance	100%	150597
1st Round	10%	15060
1st Round (Day 1)	10%	15060
2nd Round	12%	18072
3rd Round	14%	21084
Quarter Finals (Day 2)	16%	24096
Semi Finals	18%	27108
Finals (Day 3)	20%	30120

As aforementioned, the days filmed included the second day, fifth day, and seventh day, which were called Day 1, Day 2, and Day 3 respectively for simplicity of naming in this thesis. These forecasted total attendance numbers for these days were then used as a baseline to determine what percentage of the spectators had accessibility considerations. This process was carried out for both the angles of the front gate and the pedestrian village and the results are tabulated in Table 6.3 and Table 6.4.

Table 6.3: Accessibility Considerations as a % of Attendance at Front Gate

Mobility Consideration	Frequency	Screen Time (mins)	% of Attendance
Service Dog	1	0.9	0.00%
Person Needing Assistance	2	0.7	0.00%
Other	2	3.2	0.00%
Walker	4	4.3	0.01%
Roller Suitcase	17	13.8	0.02%
Crutches	18	11.6	0.03%
Oversize Luggage	18	10.0	0.03%
Walking Stick	20	9.1	0.03%
Mobility Scooter	20	9.3	0.03%
Electric Wheelchair	23	17.9	0.03%
Rollator	36	19.7	0.05%
Cane	63	52.7	0.09%
Manual Wheelchair	86	47.3	0.12%
Family with Young Children	362	342.1	0.52%
Total	672	542.5	1.0%
Total (Excluding Family with Young Children, Roller Suitcases, Oversize Luggage, and Other)	273	170.25	0.39%

Table 6.4 Accessibility Considerations as a % of Attendance at Pedestrian Village

Mobility Consideration	Frequency	% of Attendance
Walker	0	0.00%
Service Dog	0	0.00%
Crutches	6	0.01%
Electric Wheelchair	14	0.02%
Rollator	17	0.02%
Walking Stick	21	0.03%
Roller Suitcase	24	0.03%
Mobility Scooter	25	0.04%
Manual Wheelchair	41	0.06%
Cane	43	0.06%
Person Needing Assistance	65	0.09%
Other	150	0.22%
Oversize Luggage	902	1.30%
Family with Young Children	1258	1.82%
Total	2566	3.70%
Total (Excluding Family with Young Children, Roller Suitcases, Oversize Luggage, and Other)	232	0.33%

The tables above indicate those with mobility impairments represent around 0.3 to 0.4% of the spectators attending. Relative to the percentage of individuals in Canada with mobility requirements, these numbers are low which potentially indicate several considerations. Perhaps those individuals with accessibility requirements are deterred from attending a crowded event at a stadium if they are uninformed that the architectural design is inclusive and instead have presumptions about lack of accessibility at the events. Additionally, possibly individuals have attended events at the same stadium before or are familiar with the stadium layout and do not find it inclusive to their specific individual concern.

6.4.1 Demographic Breakdown by Day

Figure 6.8 and Figure 6.9 display the demographic composition of each of the matches filmed for all the accessibility cases and for only the mobility impairments respectively. The most prominent age group for mobility concerns was elderly and in the evening matches, with 13, 8, and 12 cases present on the afternoon of Day 1, Day 2, and Day 3 respectively.

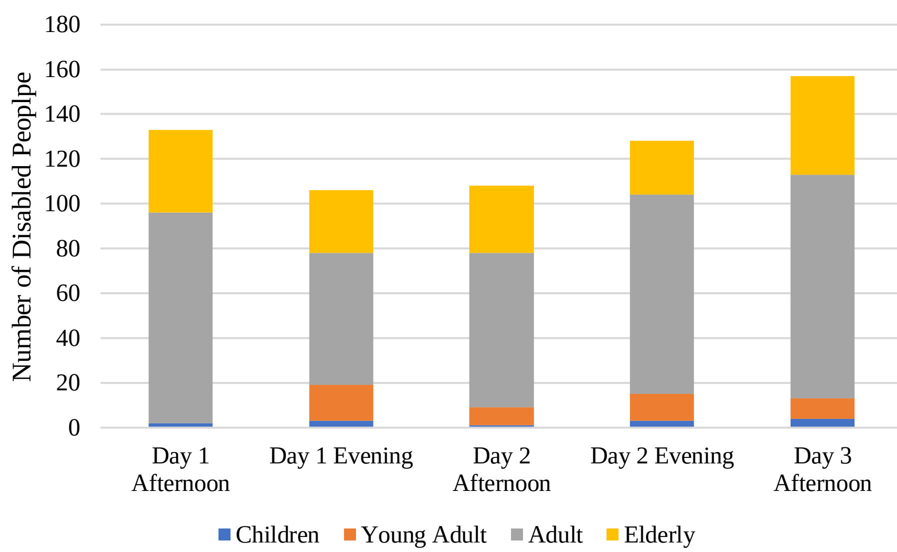

Figure 6.8: Demographic Distribution of Accessibility Cases

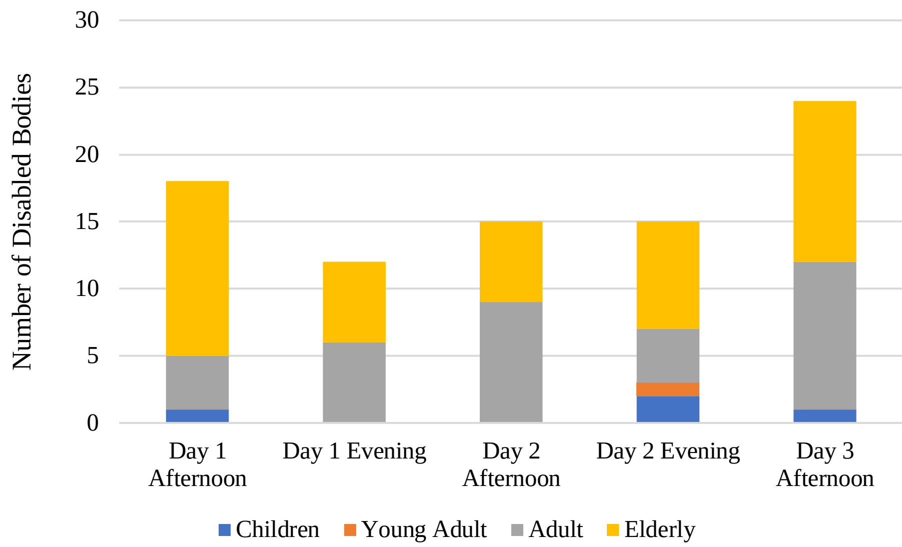

Figure 6.9: Demographic Distribution of Mobility Impairments Only

6.4.2 Consideration of Statistical Significance of Data

The data from both the front gate and pedestrian village were compiled and resulted in 505 data cases involving a mobility impairment. These data cases are summarized in Table 6.5. The final cases outlined for potential profile development are a service dog (N=1), walker (N=4), crutches (N=24), electric wheelchairs (N=37), walking sticks (N=41), mobility scooters (N=45), rollator (N=53), individuals needing assistance (N=67), canes (N=106), and manual wheelchairs (N=127). Once the agent walking speeds are determined, in which the process is outlined in the next section, a statistical analysis must be carried out to assess which data sets are significant.

Table 6.5: Compiled Data Collected (Mobility Impairments Only – Excluding Families with Young Children, Other, Oversize Luggage, and Roller Suitcases)

Mobility Consideration Compiled	**Frequency**
Service Dog	1
Walker	4
Crutches	24
Electric Wheelchair	37
Walking Stick	41
Mobility Scooter	45
Rollator	53
Person Needing Assistance	67
Cane	106
Manual Wheelchair	127
Total	505

Once the agent walking speeds are determined, in which the suggested process is outlined in the next section, a statistical analysis must be carried out to assess which data sets are significant. At the time being, the only set that can be determined to be insignificant is "Service Dog" with a sample size of one which cannot be proven significant mathematically. For the remaining sets, the walking speeds will need to be determined for all data cases before performing statistical calculations. Significance is determined on the basis of a specified confidence level, variance of the results, and a confidence interval. Since a walking speed is a result that needs to be very precise, it is recommended that a confidence level of 99% be applied. There is no value in providing a ballpark answer with any lower confidence level since that value could just be estimated or pulled from previous existing research.

6.4.3 Preliminary Agent Profiles

To provide a foundation to build the agent profiles from in future work, an example of a movement speed for one of the accessibility categories was extracted from the data. The category was chosen arbitrarily from the data to analyze a person with a cane as displayed in Figure 6.10.

Figure 6.10: Individual with Cane Egressing out Stadium's Front Gate

Next, the individuals' path of movement was observed and marked on Google Maps using the measurement tool in order to find the distance walked. This method can be improved in future work by surveying the stadium and creating a 3D model. The distance walked by the individual in was found to be 18.88 meters in total for the 55 seconds taken to walk their chosen route as displayed in Figure 6.11.

Figure 6.11: Stadium Agent Movement Mapping on Google Maps

From this information, the average walking speed of the individual was calculated with the following method:

$$\text{Walking Speed} = \frac{\text{Distance Travelled}}{\text{Time of Trip}} = \frac{18.88 \text{ meters}}{55 \text{ seconds}} = 0.34 \ \frac{\text{meters}}{\text{seconds}}$$

This data will then by categorized by demographics, including gender and age. This data point was for an elderly male. Once compilation of all data points has been collected, the nominal distribution can be obtained through an average and standard deviation of the summarized walking speeds.

6.5 Conclusions

The 500 data cases of individuals with special mobility needs collected portray a wide array of impairments in which considerations for movement in stadia need to be made. The data collected provides a vast amount of data and lays out the foundation for which specialized custom modeling profiles can be developed from. Stadium surveying, stadium model development, and analysis of walking speeds for every statistically significant test case will be considered in future work. The amount of time required to complete this future work is estimated to be 255 hours and this breakdown is outlined in Table 6.6.

Table 6.6: Estimation of Time Required for Future Analysis of Accessibility Cases

Future Work Task	Estimation of Time Required
Stadium Site Surveying	7 hours
Stadium Model Development in Google Sketchup[5]	80 hours
Stadium Model Development in MassMotion Software	100 hours
Analysis of Data Cases	68 hours (505 data points at 8 minutes a point)
Total	255 hours

[5] This projection is based on the assumption that the user is already fluent in Google Sketchup and MassMotion software. If the future researcher were not familiar with the software, it is estimated that this would require another 40 hours to account for the learning curve associated with both softwares.

Chapter 7: Conclusion

7.1 Summary of Findings

This thesis outlines novel human behaviour data collection at two stadia through multiple phases. Subsequent egress model validation using the pedestrian simulation software was performed using calibration and egress times. Although demographics and anthropometry in the stands slightly influenced the egress times, the stadium architecture was the governing factor which impeded pedestrian flow under non-emergency conditions for the first stadium of interest. Analysis of a case study fire allowed for evaluation of this conclusion during an evacuation which revealed that additional behavioural aspects of both occupant and staff, not entirely accounted for within traditional frameworks, may begin to dominate the egress simulation. Lastly, the tabulation of a database of individuals with specific accessibility requirements in stadia was collected to provide the basis for development of custom agent profiles.

7.2 Key Conclusions

The background information and literature review provided in this thesis indicated gaps in the knowledge and studies dating back decades in various human behavioural studies. The ability to design structures with efficiency while ensuring safety relies on strong knowledge of the potential behavioural outcomes still remains to be researched extensively in the context of stadia. Designs for stadia in Canada and internationally would benefit from validated numerical models to defend crowd modeling software used in the design process of stadia. Past efforts in observing crowds in stadia are limited, and thus further new validation data is required. Key contributions and findings from this thesis can be summarized as follows:

- **Chapter 3 describes footage and analysis of real crowd data that provided validation for a stadium simulation model under normal conditions.** Footage and model results show all the total egress times for the stadium studies carried out by researchers in observed trials (Trial One: 17 minutes 27 seconds and Trial Two: 33 minutes 35 seconds).
- **Chapter 3 outlines the egress observed was not of a high stress state as 96% of spectators were visibly seen to be smiling or of neutral facial expressions during egress.** All validation and predictive modeling simulations were well in excess of 8 minutes. The basis of the design benchmark that states spectators become agitated in crowds after eight minutes originates from the SCICON research, and the research carried out herein suggests this benchmark may not be realistically attainable in certain applications (Poyner, 1972).
- **Chapter 4 demonstrated demographics did not govern egress times for the stadium of interest, instead the stadium exit width capacities were the governing factor which impeded pedestrian flow under non-emergency conditions.** Although this was not an emergency situation, normal egress performance of a stadium is a baseline indicator for egress performance during an evacuation. The set of acceptance criteria for this stadium were total egress times and qualitative density assessment. Sets of acceptance criteria for stadium validation should be decided on a case by case basis and are not always transferrable.

- **Analysis of the case study fire studied in the Chapter 5 stadium allowed for authors to determine that behavioural aspects from evacuees and staff may begin to dominate egress times in a localized area in an emergency scenario.** Analysis of the behaviours in this case study include spectators not choosing to attempt to leave, despite being near the fire origin which had visible potential to spread. Twenty percent of these spectators instead decided to begin video taping the fire with their mobile phones. This study concludes that tailoring model parameters is even more important to modeling evacuations under emergency conditions where behavioural aspects may govern, as there is greater underlying uncertainty when it comes to modeling these behaviours as opposed to large-scale egress models where architecture may govern egress times. Ultimately, uncertainty associated with predicting and modeling adaptive behaviours can be reduced as this investigation reveals how behaviours can begin to be rationally controlled and considered.
- **The second phase of the research outlined in Chapter 6 consisted of novel data collection of over 500 data cases of individuals with special mobility needs which show a wide array of impairments in which considerations for movement in stadia need to be made.** study showed that these data cases represented less than 1% of the people present had physical disabilities, which indicates that people may have been deterred from attending the events if they presumed the stadium was not accessibility friendly. The data collected provides a vast amount of data and lays out the foundation for which specialized custom modeling profiles can be developed from.

7.3 Recommendations

7.3.1 Future Research

Future research will be built on the findings of the work and aim to help practitioners establish contemporary design guidance for stadium egress. For the set of experiments conducted at the first stadium, full analysis of the ingress footage was beyond the scope of this current thesis. The author of this thesis did analyze the ingress footage for total ingress times, in order to assess gate utilization before and after the event. This ingress analysis is included in Appendices A5 to A8. The ingress footage can be analyzed more in future work in which researchers can look for times required for security check ins, ticket checks, and queueing durations at the entrance.

All the footage collected in this thesis, including footage that has already been analyzed for research objectives in this thesis, has potential to be re-visited and analyzed with different research objectives. All video footage will be kept and stored securely for this purpose. A table of the footage collected throughout this thesis is tabulated in Appendix A9. These tables represent four different stadiums that data was collected at during this thesis. The tables labelled stadium two and stadium four, represent the stadia studied in Chapter 3 and Chapter 6 respectively. Stadium One and stadium three will be analyzed in future work. Should any improvements be made to any analysis software used in this thesis, future work could include re-visiting the footage and analyzing the data again which could improve the accuracy of data analysis with use of updated software. Additionally, outside influences that may impact the ability to exit will be assessed in future work. For example, Gate One of the stadium leads out to a main road, therefore impediment of this road may hinder ability to egress. To examine stress states accurately though at all stages of egress, it is recommended that a survey approach be employed in a future study in addition to monitoring other metrics. Ultimately, the modeling techniques developed will lead to a baseline performance which can be considered for fire safety.

For the stadium studied in Chapter 6, it was not the priority to test the stadium for egress, but rather collect a database of people with special accessibility needs and mobility impairments. Data collected during this phase of research included not only the accessibility data but also footage on egress of the stadium bowl. Future work can be done with this footage to compare and contrast to the results of Chapter 3 and assess whether the egress times for this stadium are governed by architecture or behavioural factors. A survey of people with mobility impairments at events at this stadium is recommended to determine whether disabled individuals feel the design in inclusive for their needs and to determine whether they had made prior visits to the stadium or if it was the individuals first time.

7.3.2 Application of Results

The findings of the assessment of the governing factor behind total egress times is transferrable and important to egress planning in the design of new and renovation of existing stadia. Stadia should be checked for the driving indicators whether that be attendance levels, demographics, architecture, or potentially behavioural and staff cues. This can be done by testing the simulation at various extreme parameters including but not limited to a range of walking speeds, a range of pre-movement times, and a range of staff prompts.

The database of accessibility concerns provided allows for an individual to look up corresponding data relating to mobility impairments of interest. The data points collected allow individuals to find cases based on not only the accessibility consideration but consider the gender, age, and any other notable factors associated with the case point. This database of 505 case points will allow a future researcher to conduct walking speed development for each accessibility case and eventually application to customized agent profiles which can be used in stadium design applications.

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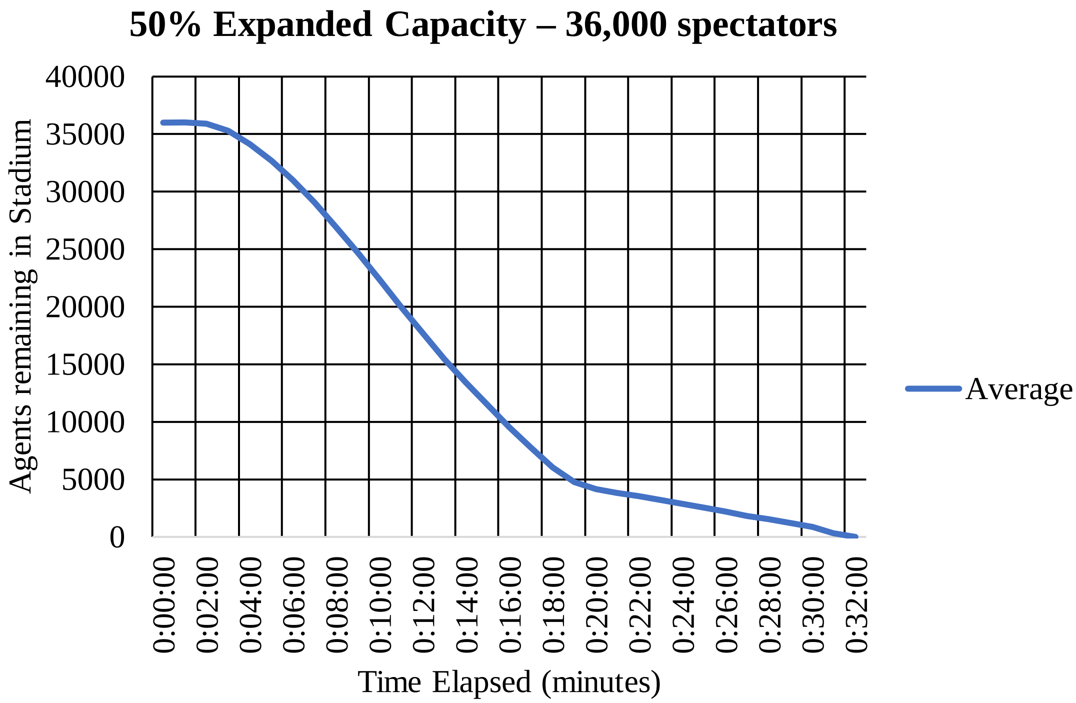
Appendix

A1: Notable Stadium Disasters

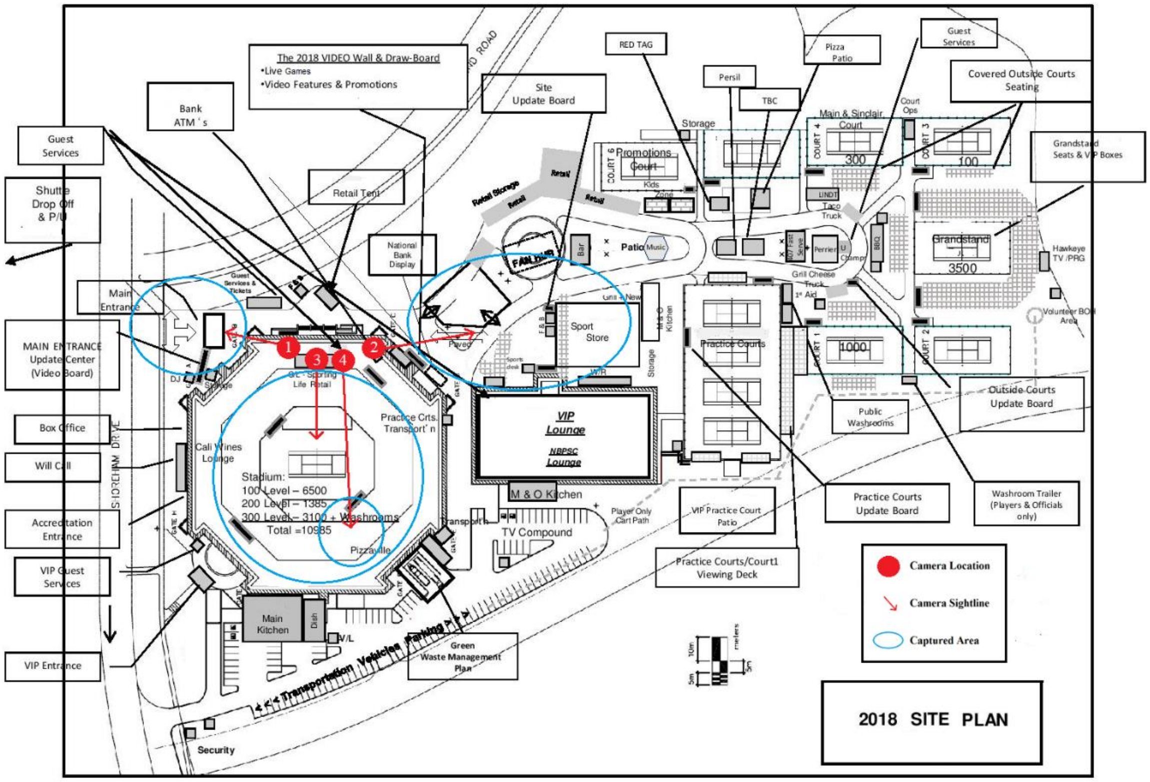
Year	Stadium Name	Category	Stadium Capacity	Number of Causalities
2017	Manchester Arena	Terrorism	14,200	22
2012	Al Masry Club/Port Said Stadium	Riot	18,000	74
2001	Ellis Park Stadium	Crowd Crush	62,567	43
2001	Djan/Accra Sports' Stadium	Riot	40,000	126
2000	Harare Stadium	Crowd Crush	80,000	13
1996	Mateo Flores National Stadium	Crowd Crush	26,000	80
1992	Armand Cesari Stadium	Structural	16,078	18
1991	Oppenheimer Stadium	Crowd Crush	23,000	71
1989	Hillsborough Stadium	Crowd Crush	39,732	96
1988	Dasarath Rangasala Stadium	Weather	15,992	93
1985	Bradford Stadium	Fire	25,136	56
1985	King Baudouin Stadium	Riot	50,093	39
1982	Luzhniki Stadium	Crowd Crush	81,000	66
1982	Estadio Olímpico	Crowd Crush	72,698	21
1981	Karaiskakis Stadium	Crowd Crush	32,115	24
1968	Estadio Monumental	Crowd Crush	66,269	71
1968	Ataturk Stadium	Riot	76,092	21
1964	Estadio Nacional	Riot	37,593	328
1946	Burnden Park	Crowd Crush	70,000	33
1902	Ibrox Stadium	Structural	50,817	25

A2: Temporary Stands Predictive Scenario



The simulation with the temporary stands erected in the model results in a 50% longer total egress time than simulation 3a at 21.25 minutes. The thesis author was utilizing a intel core i5 HP computer system, future work should include gaining access to a computer with a stronger processing power in order to simulate more runs of this scenario.

A3: Stadium Map



A4: Accessibility Categories Tracked

Individuals or groups with the following were tracked in the accessibility database:

Category	Equipment	Sample Picture[6]
Mechanical Aid	Rollator	
	Walker	
	Walking Stick	

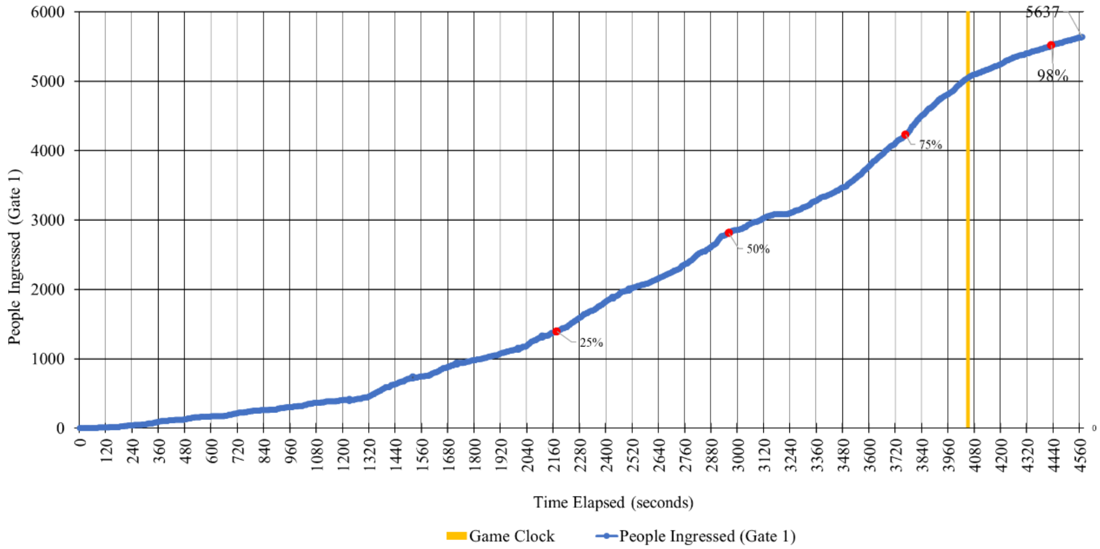
[6] All pictures used in A4 are free of copyright and free for the purpose of re-use from Google Images

	Cane	
	Wheelchair (manual)	
Electric Aid	Wheelchair (electric)	
	Mobility Scooter	

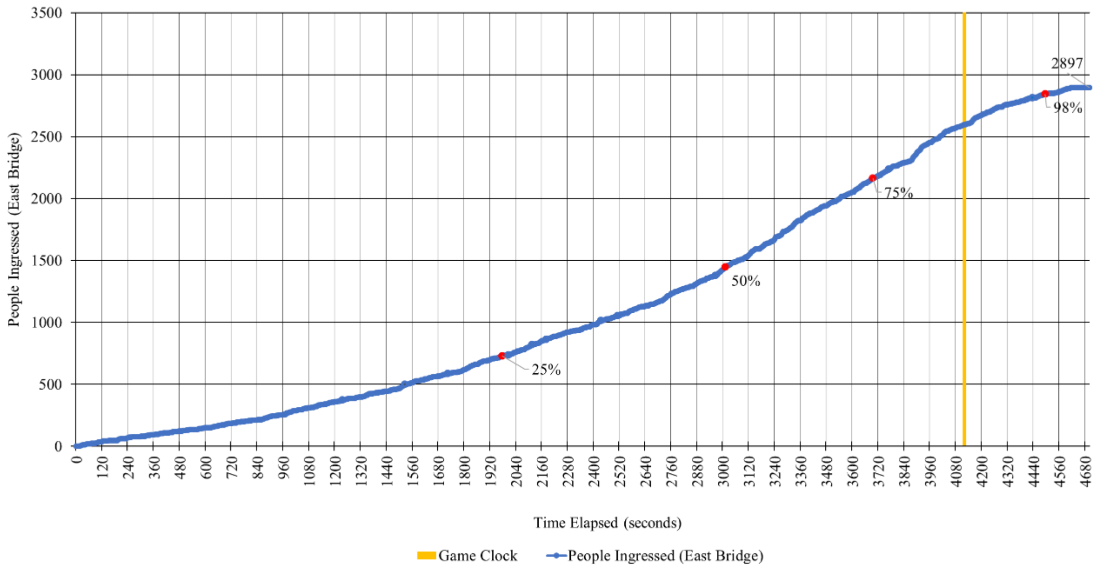
Luggage	Person with roller suitcase	
	Person with oversized bag(s) (Larger than typical day use, slowing movement speed or making movement abnormal)	 
Groups & Demographics	Families with one or more young children (carrying child, holding hand, or escorting through crowd)	

		
	Person Needing Assistance: Person with noticeable physical disabilities (using no mobility aids – ex: limp or in a brace/cast) alone or being helped by another person	
	Seeing-eye dog	

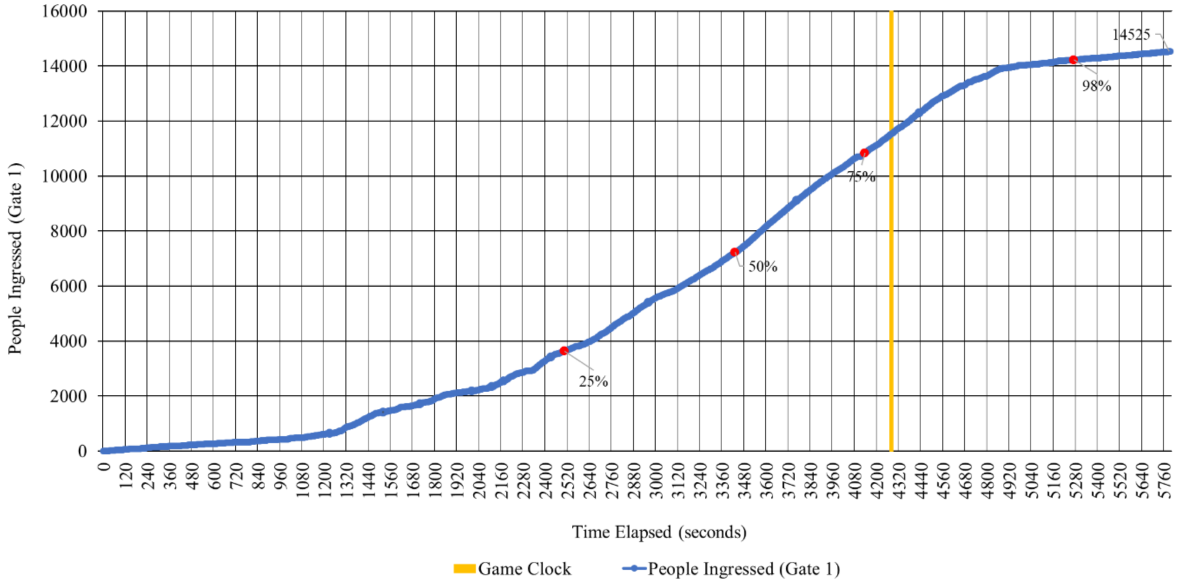
A5: Trial One – Gate One: Ingress Over Time



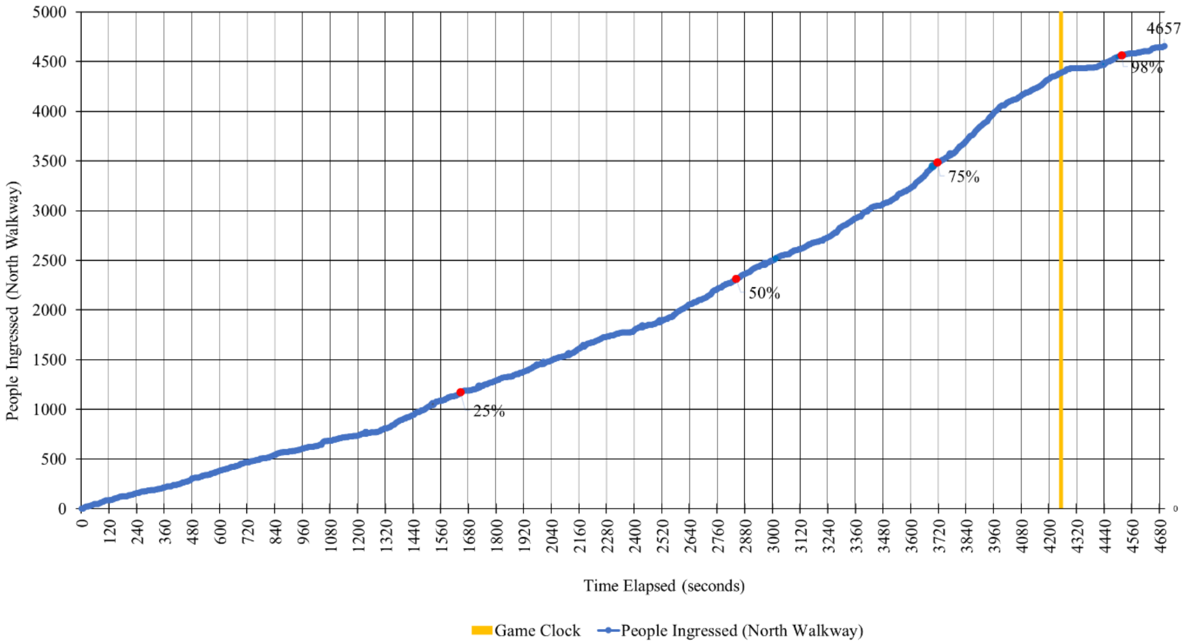
A6: Trial One – East Bridge: Ingress Over Time



A7: Trial Two – Gate One: Ingress Over Time



A8: Trial Two – North Walkway: Ingress Over Time



A9: List of Stadium Footage Obtained

Appendix 9: Footage Database for Stadium One

Month Collected	Stadium Number	Camera Filmed With	Description	Number of Clips
May 2017	1	5D	Ingress	5
May 2017	1	5DS	Ingress	5
May 2017	1	5DS	Egress	2
June 2017	1	5D	Ingress	7
June 2017	1	5DS	Ingress	7
June 2017	1	5D	Egress	3
June 2017	1	5DS	Egress	3
Early July 2017	1	5D	Ingress	7
Early July 2017	1	5DS	Ingress	6
Early July 2017	1	5DS	Egress	4
Late July 2017	1	5D	Ingress	10
Late 2017	1	5DS	Ingress	10
Late July 2017	1	5D	Egress	6
Late July 2017	1	5DS	Egress	6

Appendix 9: Footage Database for Stadium Two

Month Collected	Stadium Number	Camera Filmed With	Description	Number of Clips
September 2017	2	5DS	Ingress	5
September 2017	2	5D	Ingress	6
September 2017	2	Rebel T6 (1)	Ingress	7
September 2017	2	Rebel T6 (2)	Ingress	8
September 2017	2	5DS	Egress	3
September 2017	2	5D	Egress	3
September 2017	2	Rebel T6 (1)	Egress	4
September 2017	2	Rebel T6 (2)	Egress	4
October 2017	2	5DS	Ingress	9
October 2017	2	5D	Ingress	6
October 2017	2	Rebel T6 (1)	Ingress	8
October 2017	2	Rebel T6 (2)	Ingress	7
October 2017	2	5DS	Egress	7
October 2017	2	5D	Egress	5
October 2017	2	Rebel T6 (1)	Egress	6
October 2017	2	Rebel T6 (2)	Egress	6

Appendix 9: Footage Database for Stadium Three

Month Collected	Stadium Number	Camera Filmed With	Description	Number of Clips
October 2017	3	5DS	Ingress	5
October 2017	3	5D	Ingress	6
October 2017	3	Rebel T6 (1)	Ingress	7
October 2017	3	5DS	Egress	2
October 2017	3	5D	Egress	1
October 2017	3	Rebel T6 (1)	Egress	3

Appendix 9: Footage Database for Stadium Four[7]

Month Collected	Stadium Number	Camera Filmed With	Description	Number of Clips
August 2018	4	Go Pro	Day 1 – Main Gate	28
August 2018	4	5DS	Day 1 – Pedestrian Village	44
August 2018	4	5D	Day 1 – Stadium Bowl	66
August 2018	4	Go Pro	Day 2 – Main Gate	38
August 2018	4	Go Pro	Day 2 – Stadium Bowl	39
August 2018	4	5DS	Day 2 – Pedestrian Village	40
August 2018	4	Go Pro	Day 3 – Main Gate	39
August 2018	4	5D	Day 3 – Stadium Bowl	57
August 2018	4	5DS	Day 3 – Pedestrian Village	32

[7] Additional footage and various angles were captured and stored in addition to those listed in the table. However, the footage listed in the table are the main points of interest and therefore marked as the priority for future work.