The Analysis of Pedestrian Movement and Behaviour of Different Crowds during Stadium Egress

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Abstract
Large infrastructures and meeting points can accommodate large crowds of people. The current data used when designing for these crowds was collected decades ago and might not be applicable in today's society with a growing population. The purpose of this thesis is to systematically analyse data to investigate flow and density conditions and behavioural factors during egress of four different crowd populations at a sport stadium. This has been achieved by studying video footage of four different events recorded outside a large UK sport stadium. Observations made during the analyse showed that the type of crowd along with external factors, such as the weather, have an impact on both density, flow and walking speed. For instance, at one of the events the crowd mainly consisted of teenage girls and this crowd had the highest flow. The highest density was reached during an event with a crowd of mostly couples and smaller groups of friends who walked closely together. At this event the spectators had to stop and wait for permission to proceed and it was during these stops the density reached its maximum value. For all four events the walking speed decreased as the density increased. However, the event with the lowest density also had the lowest walking speed, which might be because of the mixture of the crowd which consisted of both elderly people and families. The event ended during the afternoon and not late in the evening which also might have been a contributing factor for the low walking speed.

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Summary

When designing for facilities made for large gatherings of people, it is crucial to have models that are up-to-date to avoid accidents due to extreme crowding. The pedestrian movement models used today are based on data collected decades ago and may therefore not be applicable for the large crowds which are more common today; for instance, demographics, cultural and social norms, and procedures may have changed over time. The most used scheme to assess space usage is Fruin's Level-of-Service (LoS), which uses a maximum density of 2,15 persons per square metre (Fruin 1971a). The LoS then maps this density to associated speeds and flow capacities. However, substantially higher values have been observed in previous studies, which calls for further studies to be able to develop a more up-to-date relationship between density and flow.

The purpose of this thesis is to analyse data recorded from a video camera during the egress at four different events on different dates at a large UK sport stadium during 2017 and 2018. From the videos the flow and density conditions in large crowds, the velocity and density conditions in large crowds, the difference in profiles between sport spectators and concert goers, and the behavioural factors regarding groups and the distance to others, have been observed. The objective has then been to compare different types of crowds egressing from a sport stadium and observe the relationship between density and flow, and between density and walking speed for large crowds, derived from the current data-sets available. To better understand the movement of large crowds and how to analyse them, a literature study was conducted. Furthermore, a visit to the stadium was made where it was decided that the area that should be analysed was at the bottom of a large ramp leading down from the stadium. With measurements collected on-site, a control area was created in the video analysis software Kinovea™. The density was then determined by counting the people present inside of the control area and the flow by counting the people leaving the control area during a certain period of time. Furthermore, the walking speed of the spectators was determined by tracking a person walking through the control area while taking the time. The data was then used to create graphs showing the relationship between density and flow and between density and velocity for the different events. During the analysis, the behaviour and demographics of the spectators were also noticed.

The results have been compared to Fruin's Level-of-Service and the guidelines available in the Guide to Safety at Sport Grounds. This shows that for these four events at this specific stadium, the densities and flows never reach the maximum values. Findings related to the differences in crowd movement and behaviour between the crowds have been reported – suggesting differences between the current data-sets and accepted practice. Subsequently density, flow and walking speed can be considered affected by the type of egressing crowd.

The conclusions of this thesis are that for this particular sport stadium in the area observed, the density never exceeds 1,85 persons/m^2 during the four analysed events. Furthermore, the demographics of the spectators along with external factors, such as the weather and time of day, have an impact on the density, flow and walking speed of a crowd. For example, it was observed that male spectators kept a greater distance between each other compared to women and couples. It was also observed that the type of clothing and the size of the body area affected the density and flow.

Sammanfattning

När man designar anläggningar som är tänkta att kunna rymma stora mängder människor så är det viktigt att ha modeller som är lämpliga till detta för att undvika olyckor på grund av extrem trängsel. De flesta modeller som används idag baseras på data som samlades in för flera årtionden sedan, vilket gör att de kanske inte alltid är applicerbara för de stora folksamlingar som är mer vanliga idag. Till exempel kan demografin och kulturella och sociala normer och människors beteende se annorlunda ut. Den teori som används mest är Fruin's Level-of-Service (LoS) vilken har en maximal densitet på 2,15 personer per kvadratmeter (Fruin 1971a). Högre värden har dock observerats i tidigare studier, vilket gör att det finns ett behov av att ytterligare studera och uppdatera förhållandet mellan densitet och flöde i stora folkmassor.

Syftet med denna studie är att analysera data som har samlats in från videofilmer av människor som lämnar en sportstadion. Filmningen har skett utanför en sportstadion i Storbritannien där fyra olika evenemang vid olika tidpunkter har analyserats under åren 2017 och 2018. Från videofilmerna har förhållandet mellan densitet och flöde och mellan densitet och gånghastighet för stora folksamlingar, samt skillnaden i demografi och beteende för olika typer av publik analyserats. Målet har sedan varit att jämföra dessa och observera förhållandet mellan densitet och flöde och mellan densitet och gånghastighet för stora folkmängder.

En litteraturstudie gjordes för att samla kunskap och få bättre förståelse för hur stora folkmassor beter sig och hur man kan analysera dem. Det gjordes även ett studiebesök till den aktuella sportstadion där det beslutades om att den videokamera som skulle användas för analysen var den som var placerad nedanför en bred ramp vilken leder ner ifrån stadion. Mätdata samlades in på plats för att sedan kunna skapa en kontrollarea i videoanalysprogrammet Kinovea^{TM}. För att bestämma densiteten räknades antalet människor som befann sig inne i kontrollarean och flödet bestämdes genom att räkna antalet människor som lämnade kontrollarean under en viss tid. Gånghastigheten bestämdes sedan genom att välja ut och följa en person som passerade genom kontrollarean och anteckna tiden detta tog. Med hjälp av den insamlade datan skapades sedan grafer som visar förhållandet mellan densiteten och flödet och mellan densiteten och gånghastigheten för de olika evenemangen. Även människornas beteende, kön, ålder och yttre faktorer, så som väder och tid på dygnet, noterades under analysen.

Resultaten som erhölls jämfördes med Fruin's Level-of-Service och med de riktlinjer som finns i The Guide to Safety at Sport Grounds, vilket visade att under dessa fyra evenemang på denna stadion så uppnåddes aldrig maxvärdena för densitet och flöde. Skillnader i hur folkmassorna rör sig och beter sig har noterats och det har även observerats att densiteten, flödet och gånghastigheten till stor del beror på folkmassans sammansättning.

De slutsatser som har kunnat dras är att för denna sportstadion och det område som har analyserats, överstiger densiteten aldrig 1,85 personer/m^2 för de evenemang som har studerats. Det har också kunnat konstateras att demografin hos folkmassan samt externa faktorer har en inverkan på densiteten, flödet och gånghastigheten. Bland annat så noterades skillnader i beteende mellan män och kvinnor samt att typen av kläder och storleken på kroppens area påverkade densiteten och flödet.

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1. Introduction

In a society where the number of people is growing and where we build larger complexes and meeting points, such as train stations, shopping centres and sport stadiums, there will be larger gatherings of people on more occasions. To avoid accidents due to crowding, it is therefore important to have pedestrian movement models that are based on current data, applicable to the large crowds we are planning for.

The current data that are used for emergency planning of large crowds was collected decades ago and may not be applicable for larger crowds in today's society given demographic, cultural, social and procedural changes. For example, one of the most common models used to describe the relationship between density and flow is Fruin's Level-of-Service (LoS), which uses a maximum density of about 2,15 persons per square metre (Fruin 1971a). However, this value is considerably lower than the maximum densities usually observed in many crowds. For instance, at the annual Hajj pilgrimages researchers gathered data between 2014 and 2015 to examine the high densities of the crowd. The results from the analysis showed that the density was above 6 pers/m^2 in some places, which is much higher than what has been recorded earlier (Löhner, Muhamad, Dambalmath & Haug 2017).

Trying to analyse large crowds in experiments can be difficult because of the limitations in both space and the number of people, and because of ethical concerns tied to this type of experiment and the safety of those involved. Instead studying real life situations where large crowds occur, it will be possible to analyse a substantially larger amount of people in a natural environment.

In this thesis, video footage of real-life large crowds has been analysed. The video footage comes from a large UK sport stadium where cameras had been set up by the UK based company Movement Strategies ltd. The cameras are situated outside, in the nearest surroundings of the stadium. Both the ingress to and the egress from the stadium were recorded during several different events on different dates during 2017 and 2018. Due to confidentiality, the name of the sports stadium cannot be revealed in this thesis.

1.1 Objective and aim

The purpose of this thesis is to analyse data from video footage that has been recorded during the egress from a large UK sport stadium through different events with different crowds at different dates. The videos will be used to investigate:

- Flow and density conditions in large crowds
- Velocity and density conditions in large crowds
- The difference in profiles between sport spectators and concert goers
- The behavioural factors regarding groups and distance to others

The objective is then to compare different types of crowds egressing from a sport stadium and observe the relationship between flow and density and between velocity and density.

1.2 Limitations and delimitations

Due to the large amount of video footage, which is estimated to be more than 8700 hrs of footage, there were limits to the amount of analysis that could be conducted, it was not possible to analyse all the data in the time-frame of the thesis. This thesis focuses only on the *egress* situations observed, and only on data collected from one camera (selected to ensure a clear view that allowed analysis to be conducted) to get a consistent analysis of the same mode of crowd movement in the same location with different crowds. Furthermore, only four different events at different dates have been chosen for the analysis, which limit the diversity of the data.

During the analysis, a control area has been used. This has been created using reference points on the ground that were identified during an on-site inspection and that can be seen in all of the videos. These reference points formed a control area which was elevated to create a grid that covered all people present inside the control area. This generates some uncertainties regarding the accuracy of the area. To be able to count all the people present inside the control area, this has been elevated which also contributes to the uncertainties of the area. The uncertainties of the area are estimated to be 50 centimetres which, considering the size of the area (108 m^2), is within a reasonable order of magnitude. Furthermore, given the large control area and the video quality, the exact number of people present inside the control area has been in some instances difficult to determine, which may have affected the results for the densities and flows. This error is estimated to be approximately 5-10 people (3-7%) during the events with high densities, and for the event with lower densities, the error is estimated to be approximately 1 person (2%). Considering the total amount of people present inside the control area, the inaccuracies are considered to be in a acceptable order of magnitude. To reduce the uncertainties regarding the number of people inside the area and the number of people leaving the it, control countings was made at every tenth measuring point.

When determining the walking speed of the people, an estimation of the distance that the people are walking has been made, due to difficulties in reconstructing the exact travel paths. The error of the walking distance is estimated to be approximately 1 metre which is considered to be a reasonable magnitude of error given the average overall travel distance of approximately 14 metres. Taking this in to account, the results of the walking speed may have been affected.

The type of flows for two of the events are categorised as: free flow, slowing down, stop, and accelerating. This categorisation is based on the authors’ personal judgement. Another analyst might evaluate the flow conditions in a slightly different way. However, the differences would probably not be major, and the results should be similar to the ones in this report.

2. Pedestrian dynamics theory

In this chapter information about pedestrian dynamics and crowd movement patterns, the fundamental diagrams and previous reaserch are reviewed and presented.

Walking with a free flow requires an even surface which is non-slippery and that an individual has enough space both longitudinally and laterally to avoid conflicts. The lateral spacing is determined by body sway and the width of the human body while the longitudinal spacing is defined by the individual spacing distance combined with perception and reaction time (Fruin 1971b). When walking in a crowd, people tend to adjust their speed and distance to others and avoid obstacles by changing direction and speed, moving in a cooperative manner (Sieben, Schumann & Seyfried 2017). The collective behaviour of a crowd emerges from the interactions between an individual and the people in their closest surroundings, where each individual is influenced by multiple neighbours (Warren 2018). Violence at stadiums can occur when spectators are gathered at sport (e.g., football games) and entertainment events. Factors that can contribute to violence is social/cultural identity, alcohol consumption and crowding. It is also known that males are more likely to engage in violent acts (Madensen & Eck 2008).

The average walking speed for adults is 0,8-1,7 m/s which reprecents a population with an even distribution of women and men (Thompson & Marchant 1995). However, there can be a large variety in people´s walking speed which depends on many factors, for example, age, physical characteristics, type of activity, and psychological state at the time. Another factor that can affect the walking speed is the density of the crowd which also varies widely. The factors that influence the density are people´s age, gender, physical characteristics, and what clothes they are wearing, for instance in the winter people have more clothes on which makes them take up more space (Predtechensky & Milinskii 1978).

When planning for events with large crowds it is important to consider how the crowd will behave during ingress, egress and in emergency situations. A crowd can be defined to be either physical or psychological where a physical crowd consists of individuals who are "physically co-present but do not share a sense of being in the same group" (Templeton, Drury & Philippides 2018, p. 3), for example commuters. A psychological crowd, on the other hand, is physically co-present but do also share a sense of being in a group, for example a group of students walking together between the same classes. Research has showed that the behaviour of a physical crowd may differ from the behaviour of a psychological crowd, especially when it comes to speed and walking distance, making it important to consider when planning for large crowds. During tests it was observed that the walking speed was lower in a psychological crowd, suggesting that the people in the crowd walked slower in an attempt to keep the formation of the group. Also, the people in the psychological crowd walked further than the people in the physical crowd and they kept closer together and formed larger subgroups within the crowd, instead of splitting up in smaller cluster as was seen in the physical crowd (Templeton, Drury & Philippides 2018).

2.1 The “fundamental diagrams”

The so-called “fundamental diagrams” show the relationship between the variable’s density, flow, and velocity that is being used to assess the performance of pedestrian facilities. The diagram helps deriving the capacity of the facility and emergency planning, as part of an engineering assessment. Research has been conducted on the topic and covering different types of facilities and flows (Vanumu, Ramachandra Rao & Tiwari 2017).

The most commonly used scheme to asses space usage, is Fruin´s Level-of-Service (LoS). The Level-of-Service originally comes from the Highway Capacity Manual and is a concept for highway design (Fruin 1971a). In this highway design there are six levels of design ranging from A to F which are based on service volumes, volume/capacity ratio, and a qualitative evaluation of driver convenience. The individual freedom to choose desired vehicle operating speed, the ability to overtake and pass other vehicles, and the freedom to change lanes are all included in this evaluation. The pedestrian Level-of-Service is based on the individual freedom to select desired walking speed, the ability to bypass slower moving pedestrians, the ease of crossing, and the presence of reverse flows at various traffic concentrations (Fruin 1971a). The standards have been developed by studies of pedestrian movements on photographs, and the classification of the standards has LoS A representing the threshold of unimpeded free flow and LoS F representing the critical density or breakdown of movement continuity (Fruin 1971b). The Level-of-Service standards for unidirectional flow on a plane surface, will be futher described below.

Level-of-Service A: When the density of people is 0,30 persons per square metre or less, the Level-of-Service is A. At this level the provided area makes it possible for people to freely choose their own walking speed, to walk past slower pedestrians and to avoid conflicts with others. The flow of people at this level should be approximately 23 persons per metre width of walkway or less (Fruin 1971a). In Figure 1 below a sketch of the pedestrian concentration at level A is presented within an area of 7 m^2.

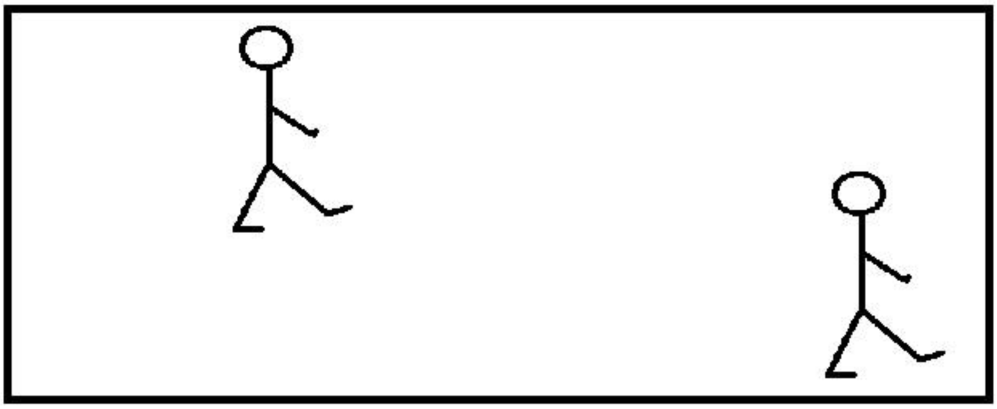

Figure 1. Sketch of pedestrian concentration at LoS A.

Level-of-Service B: When the density of people is 0,30-0,43 persons per square metre, the Level-of-Service is B. At this level the provided area makes it possible for people to select normal walking speed and to walk past other pedestrians who walk slower in primarily unidirectional flows. In places where reverse direction or pedestrian crossing movements occur, minor conflicts will happen, which will slightly lower the mean pedestrian speed and potential volumes. The flow of people at this level should be approximately 23-33 persons per metre width of the walkway (Fruin 1971a). In Figure 2 below a sketch of the pedestrian concentration at level B is presented within an area of 7 m^2.

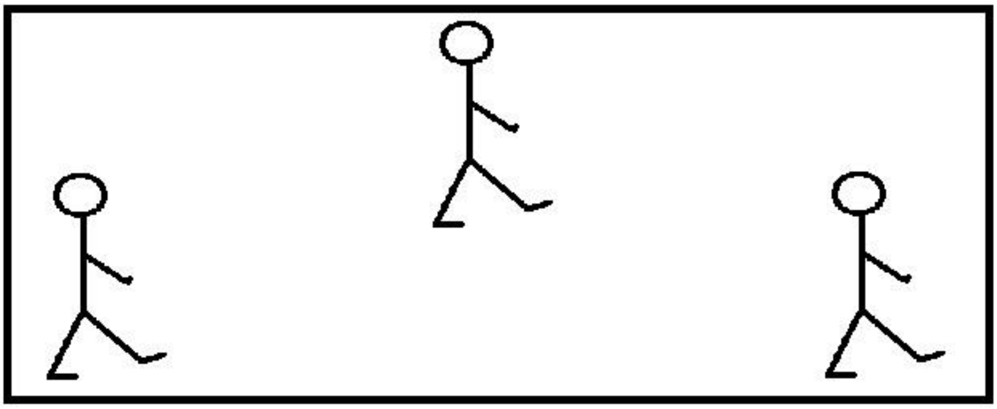

Figure 2. Sketch of pedestrian concentration at LoS B.

Level-of-Service C: When the density of people is 0,43-0,71 persons per square metre, the Level-of-Service is C. At this level the provided area makes it restricted to select individual walking speed and freely pass other pedestrians. There is a high probability of conflict where adjustment of speed and direction are needed, at places where reverse flows and pedestrian cross movement exist. The flow of people at this level should be approximately 33-50 persons per metre width of the walkway (Fruin 1971a). In Figure 3 below a sketch of the pedestrian concentration at level C is presented with in an area of 7 m^2.

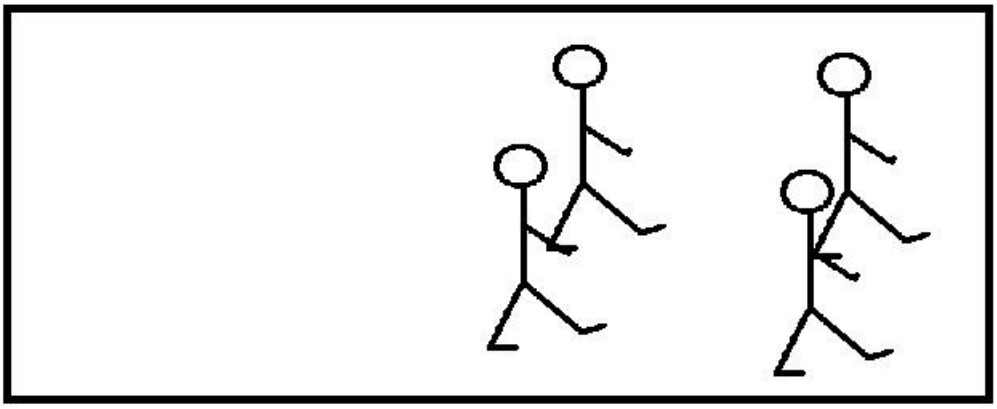

Figure 3. Sketch of concentration of people at LoS C.

Level-of-Service D: When the density of people is 0,71-1,11 persons per square metre, the Level-of-Service is D. At this level the provided area will, due to difficulties in passing other pedestrians and avoiding conflicts, make the majority of the people´s normal walking speeds restricted and reduced. People who are involved in crossing movements and reverse-flow will have multiple conflicts and be very restricted. The flow of people at this level should be approximately 50-67 persons per metre width of the walkway (Fruin 1971a). In Figure 4 below a sketch of the pedestrian concentration at level D is presented within an area of 7 m^2.

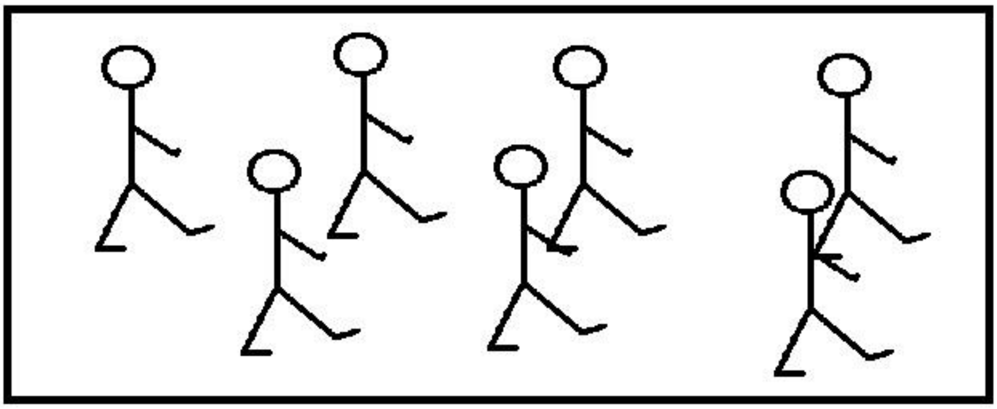

Figure 4. Sketch of concentration of people at LoS D.

Level-of-Service E: When the density of people is 1,11-2,15 persons per square metre, the Level-of-Service is E. At this level the provided area will make all pedestrians lose their normal walking speeds which will require frequent adjustments to gait. Walking forward will only be made by shuffling in the lower end of the density range and there will be no availiable place to bypass slower moving people. Pedestrians attempting reverse-flow and cross-flow movement will experience extreme difficulties. The flow of people at this level should be approximately 67-83 persons per metre width of the walkway. This value will approach the maximum capacity of the walkway, which results in frequent stops and interruptions of flow (Fruin 1971a). In Figure 5 below a sketch of the pedestrian concentration at level E is presented within an area of 7 m^2.

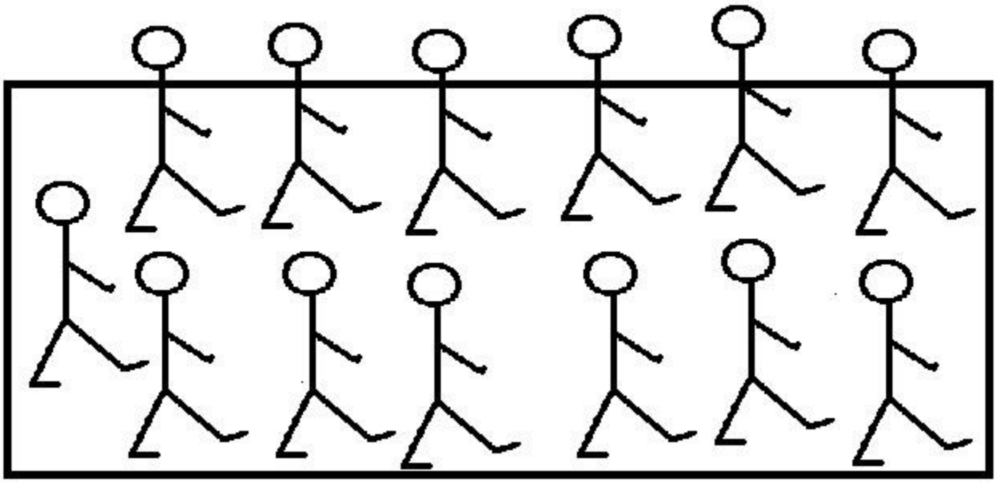

Figure 5. Sketch of concentration of people at LoS E.

Level-of-Service F: When the density of people is 2,15 persons per square metre or more, the Level-of-Service is F. At this level the provided area will make all pedestrians have extremely restricted walking speeds, and walking forward can only be made by shuffling. Reverse or crossing movements will be impossible and frequent unavoidable contact between pedestrians will occur. This level is representative of complete breakdown in traffic flow and loss of control. Pedestrian areas that are more then 2,15 persons per square metre can better be represented as queuing rather then a flow (Fruin 1971a). In Figure 6 below a sketch of the pedestrian concentration at level F is presented within an area of 7 m^2. As can be seen in the picture the local density is higher than the density for the whole area, so even if the density for the whole area just exceeds 2,15 persons per metre square, the local density, which is the one that affects the people, is much higher.

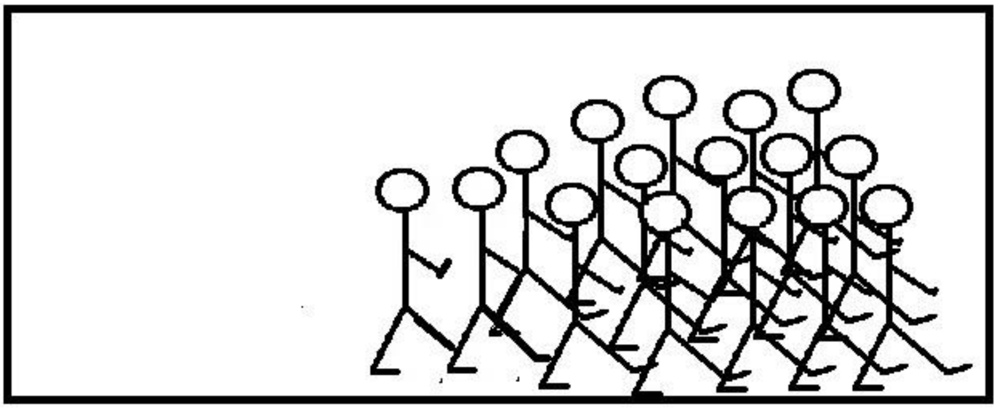

Figure 6. Sketch of concentration of people at LoS F.

For several decades the fundamental diagrams have been the focus of much research. Many researchers have compiled data and measured the density, flow and velocity of people in different places. The data available is mainly for low densities due to the difficulties, and dangers, with setting up experiments and perform field studies for high densities (Löhner, Muhamad, Dambalmath & Haug 2017). Below are five different studies presented regarding density and flow, both experimental and field studies.

During the Hajj pilgrimages of 2014 and 2015 to Mecca, research took place to measure the high densities of the crowd. The pilgrims performed the so-called Tawaf by walking seven times around the Kaaba (a building situated at the centre of Islam´s most important mosque), which is placed at the centre of the Sahn (the courtyard of the mosque). To be able to analyse the density the researchers put up video cameras and filmed the pilgrims. When analysing the data, a grid with a cell size of approximately ten square metres was constructed over the area. When determining the density, a manual count of the people inside the cell was performed. To obtain the velocity the researchers followed a person walking through one cell and measured the time it took. From these data points they derived a density and velocity relationship which showed that the density is much higher than what has been recorded earlier, 6 pers/m^2, and that the velocity did not vanish despite the high densities (Löhner et al. 2017).

Another case study was conducted at the Masjid Jamek LRT Station in Kuala Lumpur, Malaysia, in an attempt to assess and simulate the pedestrian movement in an enclosed space of public transport infrastructure. First, information about the pedestrian’s demographic, walking speed and wayfinding in the station was collected by using a combination of cameras and manual counting. The travel time and walking speed were determined from the cameras by using Microsoft Excel and the video analysis softwear Siliconcoach, while gender, age, physical attributes, and familiarity were collected manually. The output was then used for a simulation development in SimWalk to provide a comprehensive analysis on the pedestrian crowd movement and volume in the station. The results showed that pedestrians walk faster on a straight route compared to a irregular path, but also that gender, age and familiarity had an influence on people´s walking speed when moving in the concourse area of the station (Bohari, Bachok & Osman 2016).

As part of the research project BaSiGo, which develops safety and security modules for large gatherings, the appearance of critical conditions due to overcrowding was studied in June 2013. More then 2000 test subjects participate in the experiments which took place during four days in a hall at the exhibition site in Düsseldorf, Germany. One of the experiments that was made during these days focused on entrances to music events where pushing by highly motivated fans can lead to dangerous situatons. During the experiments the behaviour of the crowd and the influence of the spatial arrangement of the barriers were studied. One of the setups that was used during the experiment was without any guiding barriers and the participants were placed randomly in a half circle in front of the two entrances. For the other setup, a corridor was built to guide the partcipants in a limited space from the side to the entrance. Insde the corridor the test persons was positioned loosely and not in a certain order. The participants were told in both of the setups that they should imagine an entry situation to a concert of their favourite artist. They were then told that the entrance should open soon and that they should try to be the first ones in – in an attempt to motivate their movement. The investigators then commmanded the doors to be opened and the participants started to enter. When the entry started, the density increased fast from 3,8 pers/m^2 to 8 pers/m^2 during the first 10 seconds at the setup with no barriers. After the start signal, all of the people moved towards the entrance until all free space was occupied. For the setup with the corridor, the density did not increase that much, and after 20 seconds the density was 5 pers/m^2 (Sieben, Schumann & Seyfried 2017).

At the Central Institute for Applied Mathematics of the Research Centre Jülich, experiments regarding the relationship between densities and velocity of pedestrians were performed. The experiment was for single file movement in a corridor. To set up the corridor the researchers built a path with chairs and ropes that formed a circle. When collecting the data video cameras were set up to film the test persons and an automated analyse procedure was used. The results from this experiment showed that for single file movement the density and velocity is similar in a laboratory environment as in real life (Seyfried, Steffen, Klingsch & Boltes 2005).

In Japan, another experiment was conducted where the participants were passing through openings with different width. The results showed that the flow ranged between 149,4-155,4 pers/m*min (Fujii et al. 2017).

Another method for examining pedestrian space is the time-space concept where the time-space is a product of an area (or space) and a time period (Gregory & Benz 1986). The method assumes that areas used by pedestrians can be considered to be time-space zones in which the pedestrians require a different amount of space, depending on their activity. The space needed is also occupied for different periods of time. For example, a pedestrian standing still, will require less space then a pedestrian walking through a room, but the pedestrian that is walking will only occupy the space for a relatively short period of time. The method divides pedestrian activities into three catogories: walking, waiting, and processing, and to determine if a facility is adequate for a specific use, the amount of time-space required for an activity can be summarised and then compared to the amount of time-space available.

The time-space required for walking is a function of the walking speed, the walking distance and the number of people walking in the specific area. The walking speed is affected by factors such as the gender and age of the pedestrians, however people are familiar or not with the facility, the weather conditions, and the purpose of the walk. For example, commuters that are familiar with their path generally walk faster than a tourist who may not be familiar with the facility or who carries luggage. The time-space required for waiting is a function of the space that each person requires, the time spent waiting, and the number of people who are waiting. The amount of space that a person requires depends on the duration of the time spent waiting or queing, but also on factors such as, gender, age and the type of facility. The third category is called processing and includes all activities where a person is performing a transaction or process that involves a more complex action, for example, buying a ticket, or stopping to read a map. Here the time-space required is a function of the space that each person require, the amount of time that the space is required and the number of people who are involved in the activity.

When defining the time-space zones in a facility it is important to distinguish between used and unused areas. Used areas is defined as space that can “be used or which is available for use” (Gregory & Benz 1986), by the persons involved in the activity while unused space is, for example, areas occupied by furniture or obstructions such as columns, garbage cans, luggage or strollers. For calculating the time-space, a time-period when the pedestrian activities are intense should be selected as this will represent the peak or the worst case conditions in the facility (Gregory & Benz 1986).

3. Regulations

In the UK the regulations used when dimensioning a sports stadium is the Guide to Safety at Sport Grounds, also called “the Green Guide” (SGSA 2018). The guide is an advisory document that applies to the safety of all people that are present at any sport grounds and it is the management of these sport grounds that has the primary responsibility for the safety. The guide also provides guidance to improve safety at existing grounds, both in terms of design and safety management. Findings from this thesis might have implications for future regulations and the assumptions that they make.

When dimensioning the capacity of an exit system or an emergency evacuating system the flow rate (also known as rates of passage) is used. The flow rate is the number of people who can pass through a particular point in an exit system, or an emergency evacuating system, in a given time. According to the regulations there are several factors that can affect the flow rate, such as: the gender and age of the spectators, if there are any children present or spectators with disabilities, locations of toilets and television screens along the route, the number of stairways, weather conditions, the availability of alcohol, and the outcome of the event. When calculating the capacity for an exit route on a level surface the recommended maximum flow rate is 82 spectators per metre width per minute. It is however, also emphasised that a more comfortable circulation can be achieved by basing the design of a level circulation route on calculations of flow rates of fewer than 82 persons per metre width per minute.

Furthemore, it is recommended that the average crowd density should be no more than 2,0 persons per square metre in general concourse areas. This level of density is considered to be comfortable enough for people to be able to eat and drink, or use their mobile devices and still retain sufficient space to other people. Higher densities are accepted in certain areas for a short period of time, such as around bars and food counters where queues form. However, the preferred maximum crowd density for standing spectators and people queuing is 4,0 persons per square metre. These values are based on an adult, average sized male that occupies an area of 0,14 square metres which makes it necessary to adjust the figures if, for example, the spectators wear bulky winter clothes, or if there are many children present at the event (SGSA 2018).

4. Methodology

A theory and literature study was conducted to collect information from previous research of movements of large crowds and the methods for identifying their fundamental relationship as well as factors which may lead to critical conditions. Further, a visit to the stadium was made to decide which reference camera to use and which events to analyse. The stadium where the videos have been recorded is a large UK sport stadium used for various events, such as football games, rugby games and music concerts, at which it is possible to purchase food and alcohol. The stadium is positioned on an elevation and leading down from the stadium, there are several different walkways, with the mostly used one at the front-end outside of the building. This route consists of two straight ramps leading down from the stadium to a horizontal wide walkway in asphalt, which is about 1 kilometre long and where most people choose to continue straight forward during egress. Directly below the ramps, the walkway is about 30 metres wide for about 50 metres and after that the walkway is about 26 metres wide for the rest of the way. Along both sides of the walkway there are buildings which accommodates apartments and student housing. At the bottom of the ramps people coming out from other exits, on the ground level, can merge with the crowd coming down by the ramps which increases the number of people walking along the horizontal walkway. One of the ramps is shown in Figure 7.

Estimations made by Movement Strategies ltd indicate that the ramps are used by about 30% of the visitors during egress, meaning nearly 27 000 people during a sold-out event. For the safety of the spectators the stadium uses a Stop-and-Go system during egress. However, the system is only used during events when the density is estimated to be high. The system works in such a way that stewards are placed with regular intervals along the whole walkway. When the stewards controlling the egress at the end of the horizontal walkway estimate that the density of the crowd gets too high, they contact the stewards further up on the walkway who then stops the people. The first group of stewards are situated about 40-50 metre from the ramps and because of this, the people present inside of the analysed area are affected by the Stop-and-Go system. When the density is reduced to a sufficiently low level, people in the back are allowed to continue their egress. For two of the events that has been analysed, the Stop-and-Go system was used. The flows for these events have been categorised into four categories: free flow, slowing down, stop and accelerating. Because of the size of the control area, the different types of flows had to be defined as when the majority of the people inside the control area is moving with a certain type of flow. Free flow is when people walk unimpededly and it is an even flow inside the control area, slowing down is when at least 50% of the people inside the control area are slowing down their walking speed, stop is when nearly all of the people inside the control area are standing still and accelerating is when at least 50% of the people inside the control area have started to walk after the stop. A more detailed description of the different types of flows is presented in Chapter 5.

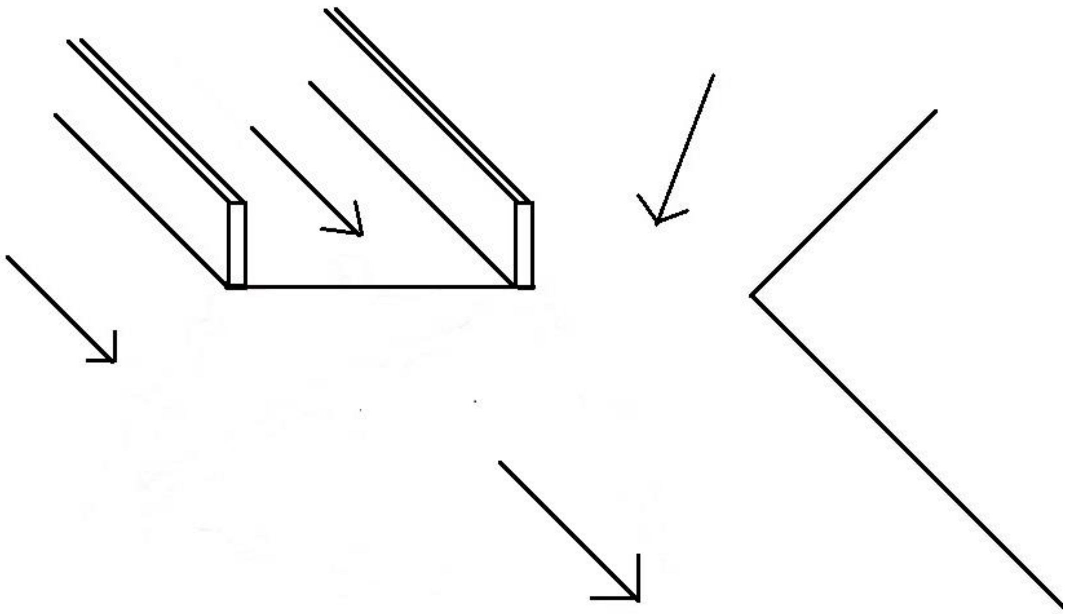

Figure 7. Setup at the stadium showing the bottom at the ramp and the beginning of the horizontal walkway.

The video footage used in the analysis comes from one out of several cameras placed at different locations on the outside around the whole building and in the closest surroundings, with cameras along every walkway leading to and from the stadium. The cameras have been set up by the UK company Movement Strategies ltd to overlook the ingress and egress, which means that they are placed in a way that they overlook the crowds of people walking both up to and from the stadium. The recordings have been made during several events over a long period of time during the years 2017 and 2018, which gives a variation of people considering both age, gender and behaviour. The camera that was selected is the one that covers the area below one of the ramps and the beginning of the horizontal walkway at the front of the stadium. The ramp is about 11 metres wide and 100 metres long. This camera was selected due to the good angle and because it shows one of the most crowded places during egress. The area recorded and its closest surroundings was also free from obstacles which enables people to walk with a free flow without interruption. Measurements were collected during the visit to the stadium to enable the creation of a control area at the bottom at the ramp which was used during the analysis, see Figure 8. The area of the control area was determined by splitting it up in two triangles. Their areas were then calculated by using Heron's formula which states that the area of a triangle can be calculated using Equation 1:

$$A = \sqrt{s(s-a)(s-b)(s-c)} \qquad \text{Equation 1}$$

Where a, b and c are the lengths of the triangles sides and s is the semi-perimeter of the triangle which is calculated using Equation 2:

$$s = \frac{1}{2}(a+b+c) \qquad \text{Equation 2}$$

The area of the control area was then determined to be 108 m^2 by summing the areas of the two triangles. Furthermore, the video footage from the selected camera was studied and the data were analysed to receive a density, flow and velocity. While studying the video footage the gender, age and behaviour of the crowds were also observed and noted for all four events.

The software Kinovea™ was used to analyse the data. The software is a video player normally used for analysing sport, with features like slowing the video down and draw in the picture (Kinovea 2018-11-07). When determining the densities over time at the different events, a control area has been drawn in the videos using a perspective grid, as seen in Figure 8. The grid has been laid out in the videos to match the control area by using features on the ground that can easily be seen in all the videos. It has then been elevated to make it possible to count the people located inside the control area, as seen in Figure 9. The elevation is necessary since there is a perspective in all the video footage and it is therefore needed to cover the people located at the foot of the ramp and on the right side along Line 2. People in the videos have been used as reference points to determine the height of the elevation, making sure that everyone located inside of the actual control area is also covered by the grid. The number of people inside the control area has then been determined by counting the number of heads seen inside of the lines of the elevated grid.

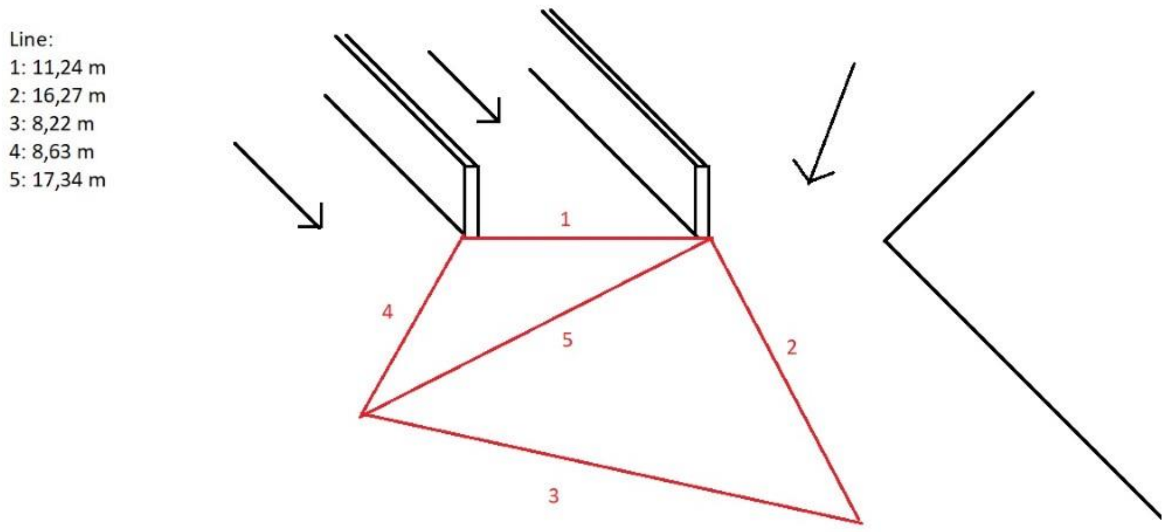

Figure 8. Sketch of control area with measurements.

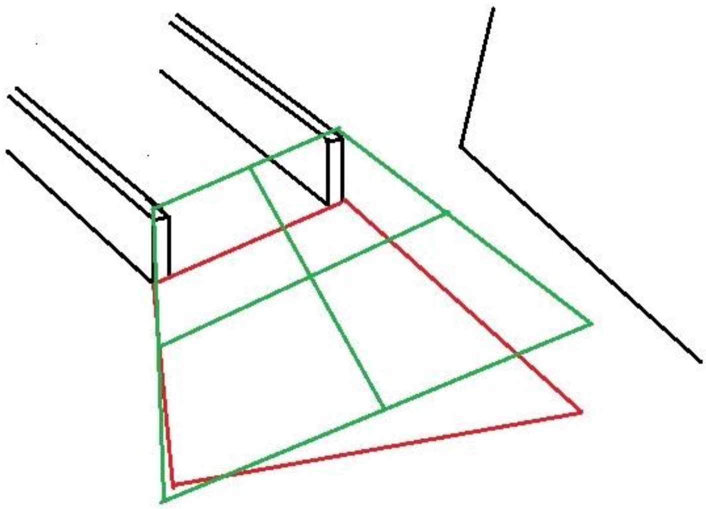

Figure 9. Sketch of elevated grid above the control area.

The procedure to determine the density and the flow has been the same for all four events. When the elevated grid has been laid out the video has been played to when the egress starts. The video has then been paused and the number of people inside the control area has been counted. The numbers have then been entered to a spreadsheet in Excel where the density has been calculated by dividing the number of people with the area of the control area giving the density in persons per square metre, as seen in Equation 3.

$$\rho = \frac{Number\ of\ people\ inside\ of\ the\ control\ volume}{Area\ of\ the\ control\ volume} \qquad \text{Equation 3}$$

Furthermore, the video has been played for ten seconds while the number of people leaving the control area over the grid-line located closest to the camera (grid-line over Line 3) has been counted. These numbers, including the start and stop time for every datapoint, have also been entered to the spreadsheet where the number of seconds has been converted to minutes. The flow has then been calculated by using Equation 4 where the number of people has been divided by the number of minutes and the length of the line, which gives the flow in persons per metre per minute.

$$f = \frac{Number\ of\ people\ passing\ over\ the\ line}{Time * Length\ of\ the\ line} \qquad \text{Equation 4}$$

When performing these countings, one person was counting the people and the other one kept track of the time in the video. To reduce uncertainties, a control counting was made at every tenth measuring point by both analysts.

After all the densities and flows had been calculated the velocity was determined in the same way for all four events. The pedestrian walking speed can be determined by dividing the distance a person has walked with the transit time, giving the velocity in metre per second (Goh, Subramaniam, Wai & Ali 2012). First the distance between Line 1 and Line 3 was estimated to be 14 metres. Then the video was fast-forwarded to the start time for the first datapoint where one person was identified and followed while walking through the control area. The time when the person entered and left the grid was noted, giving the number of seconds needed to walk through the control area. This procedure was then repeated for several datapoints at different densities for all four events. The numbers were entered to a spreadsheet where the velocity was calculated by using Equation 5 where the distance (14 metres) has been divided by the number of seconds it took for the person to walk through the control area.

$$v = \frac{Distance}{Time} \qquad \text{Equation 5}$$

From the numbers in the spreadsheet graphs showing the relationship between density and flow and between density and velocity could then be created for all four events by using the software Veusz™. When creating these graphs, a regression was made to be able to compare the different events with each other. To determine which type of trendline that should be chosen, the function R^2 was used. The R^2 describes how well the curve is fitted to the scatterplot and therefore the trendline which gave the highest R^2 values for the majority of the events was the trendline that was used.

5. Analysis of data

The four different events that have been analysed will be further presented in this chapter, including a description of the audience attending the different events and their behaviour during the egress. In two of the events the Stop-and-Go system has been used, which results in a different type of density and flow relationship than the events without. For the events where the Stop-and-Go system is used, the flows have been categorised in four categories: free flow, slowing down, stop and accelerating. Because of the size of the control area, the different types of flows had to be defined as when the majority of the people inside the control area is moving with a certain type of flow. Free flow is when people walk unimpededly and it is an even flow inside the control area, slowing down is when at least 50% of the people inside the control area are slowing down their walking speed, stop is when nearly all of the people inside the control area are standing still and accelerating is when at least 50% of the people inside the control area have started to walk after the stop.

5.1 Football game

This event was a football game between a British and a foreign team. It took place during the winter and the game ended late in the evening. Most of the people in the audience were men, but there were also a few families with children and a few couples typically formed of an adult male and adult female. The age distribution is estimated to have ranged mostly between young adults to people in their fifties or sixties, with only a few children present. The videos also showed that most of the people were either walking alone or in smaller groups of two to four people. Some parents were holding their children by their hand and the families seemed to keep together in the crowd. It also seems that people were able to keep a distance to each other during the egress, which allowed them to move without any major conflicts and kept the flow fluent. Due to the season, most people were wearing winter clothes.

At this event the Stop-and-Go system was used and in Figure 10 below a diagram of the relationship between the density of the crowd and the different categories of flows is presented. From the diagram it can be seen that during free flow, the flow increases as the density gets higher up to a certain point. When the density reaches 0,6 pers/m^2 the flow stops rising and stays at approximately 50 pers/m*min. The flow starts to decrease when the density reaches a value of 0,9 pers/m^2 and starts to rise again when the density gets higher than 1 pers/m^2. People start to slow down when the density is 0,7 pers/m^2, which indicates that the Stop-and -Go system is used. The slowing down continues with a decreasing flow and an increasing density until the density reaches approximately 1,1 pers/m^2 and the flow is near 0. At a density of 1,3 pers/m^2 the flow goes from slowing down to stop and from the diagram it can be seen that during stop the density increases until it reaches 1,6 pers/m^2. After the stop the category of flow changes to accelerating and as can be seen in the diagram, both the density and flow are high during accelerating. The maximum density and flow that occurred during this event was 1,6 pers/m^2 and 52,6 pers/m*min which is level E according to the Level-of-Service standards.

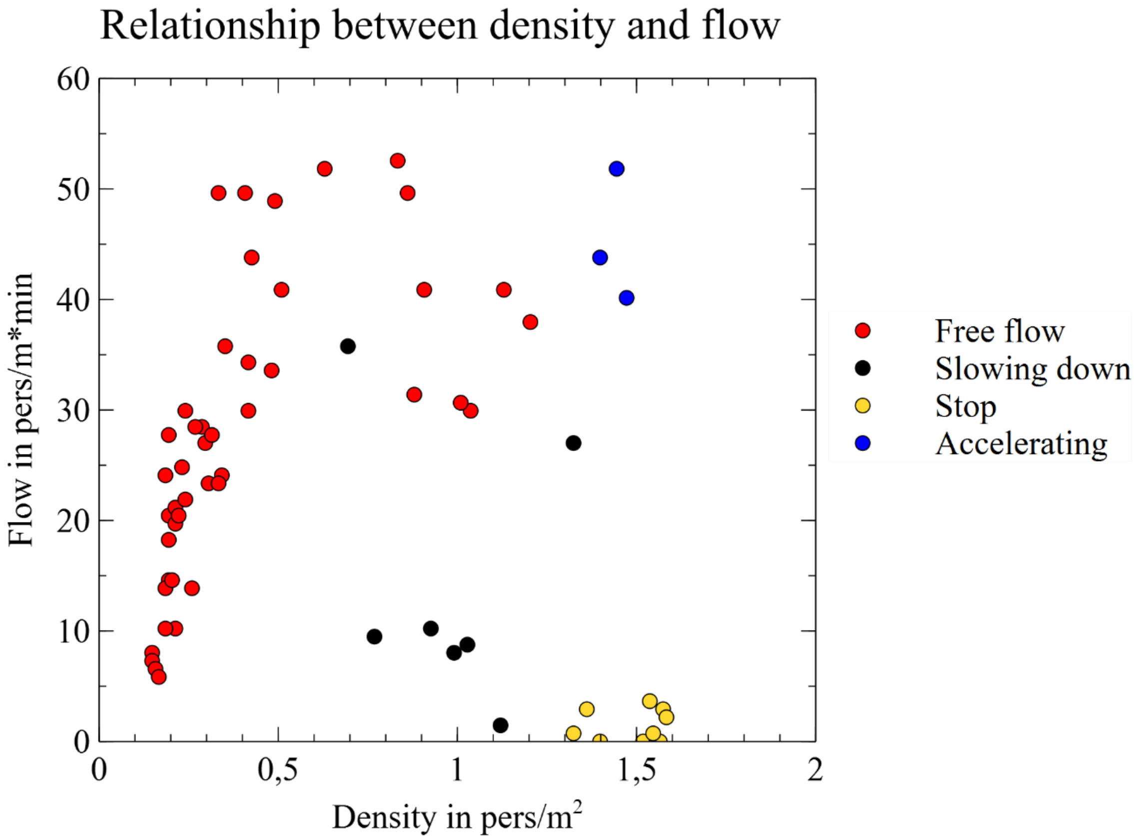

Figure 10. Diagram of the relationship between density and flow with the different flow categories presented.

In Figure 11 below the relationship between density, flow and time of the day is presented as a diagram. The timeline is added to enable a view of how the density and flow changes over time. From the diagram it can be seen that during the early egress both the density and flow are low and as the egress proceeds the density gets a little higher and the flow increases a lot. When the egress has been going on for approximately 30 minutes, the Stop-and-Go system is used which increases the density and the flow goes down to 0. When people are allowed to walk again the flow gets high and then both the flow and density decrease as the egress proceeds.

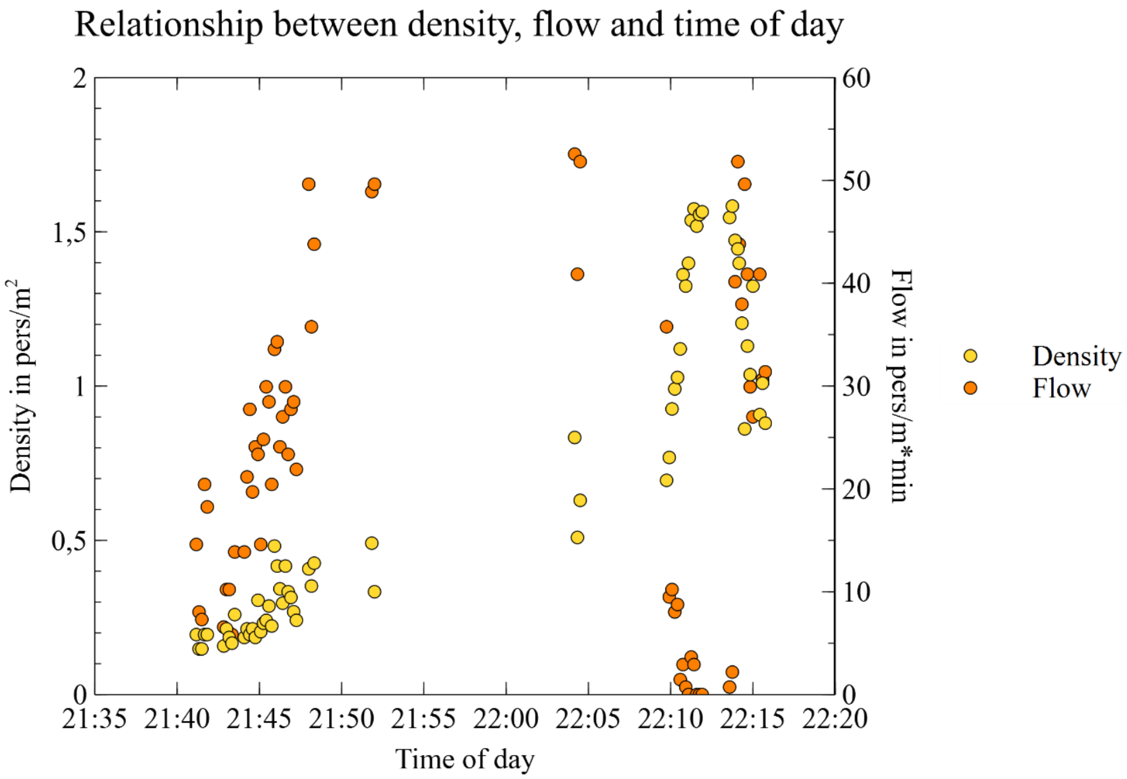

Figure 11. Diagram of the relationship between density, flow and time of day.

5.2 Rugby game

This event was a rugby final between a foreign and a British team. The event took place at the end of the summer and the game ended in the afternoon. Spectator ages ranged from young adults to people in their sixties or seventies. The audience mainly consisted of men walking together in smaller groups of two to five people. However, the distribution between genders was more equal than the football game, with quite a lot of couples and families with children present. Many of the couples were holding hands and in the families most of the parents were holding their children by their hand. Since the density never reaches any high values during this event, there was a lot of space for everyone to walk free and avoid conflicts which resulted in an even and free flow during the egress. This also allowed people to talk more easily to each other while walking and seemed to make it easier to stick together in their groups. Due to the time of the year, most people were dressed in summer clothes.

During this event the Stop-and-Go system did not need to be used and therefore the flow was free during the whole egress. In Figure 12 below the relationship between density and flow for the egress from the rugby game is presented as a diagram. It can be seen from the diagram that the data points almost form a linear relationship between the density and flow. When the density is low the flow is also low and as the density increases so does the flow. For this event the maximum density reaches 0,55 pers/m^2 and the maximum flow 42,5 pers/m*min, which represents Level C at the Level-of -Service scale.

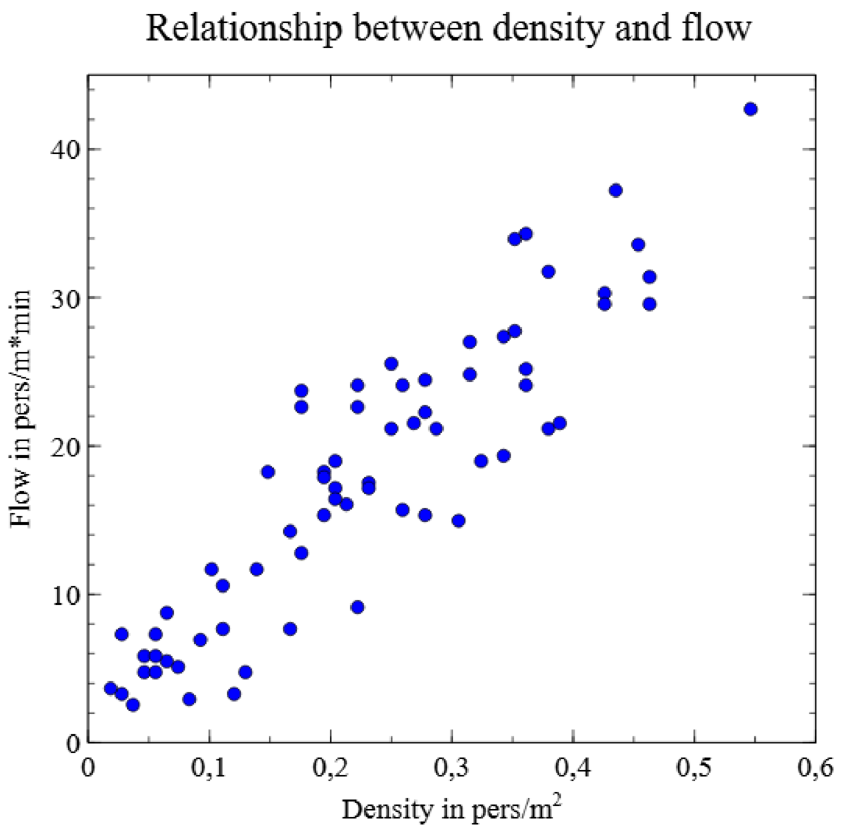

Figure 12. Diagram of the relationship between density and flow.

In Figure 13 below the relationship between density, flow and time of day for the event is presented as a diagram. Also, here the timeline is added to enable a view of how the density and flow changes over time. During the early egress both the density and flow are low and as the egress proceeds both the density and flow increase. After 15 minutes of analysing the video, the maximum density and flow was reached. Both the density and flow started to decrease after the maximum was reached and continued to do so until the egress was finished.

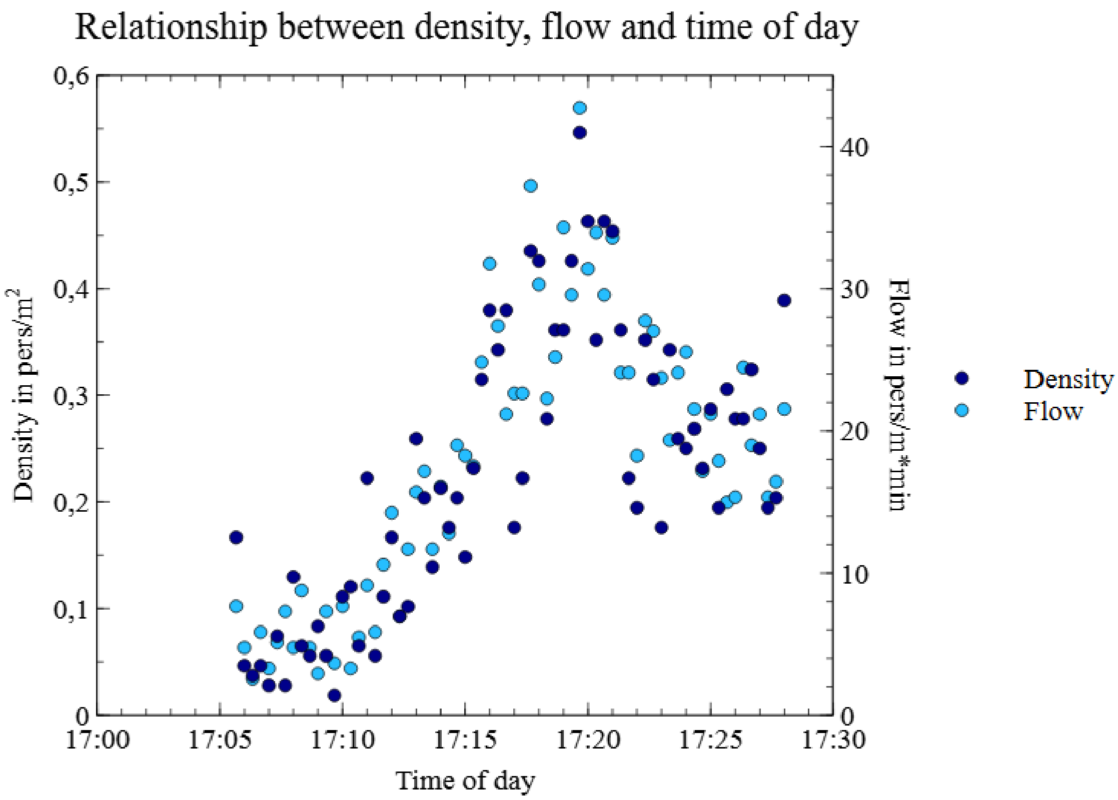

Figure 13. Diagram of the relationship between density, flow and time of day.

5.3 Concert with male singer/songwriter

This event was a concert with a world known male singer/songwriter. The event took place in the summer and the concert ended late in the evening. The audience consisted of both men and women and the estimated age ranged between young adults to elderly people in their seventies. People mostly walked in couples holding hands or in larger groups of both women and men. No families or children could be seen in the videos and the distribution between genders seemed to be quite equal. At this event the Stop-and-Go system was used, which made people slow down and then stop. Even though people leaving the stadium were walking down the ramp during the stop, it did not seem to be too crowded for the people who were standing still in front of the ramp. People still had space around them and pressure from the people in the back did not seem to exist. Due to the season, most people were wearing summer clothes.

In Figure 14 below the relationship between density and different categories of flow are presented. When the density is low during free flow, the flow is also low and as the density gets higher so does the flow. The density reaches a maximum value of 0,5 per/m^2 for free flow with a maximum flow of 55,5 per/m*min. As the density gets higher the flow decreases a bit and stays in the range of 36-48 pers/m*min. The slowing down occurs when the density is 0,5 – 1,5 pers/m^2 and as mentioned before this is because of the Stop-and-Go system. The density during the stop varies from 0,6 pers/m^2 to 1,8 pers/m^2. During accelerating the density ranges between 0,8 pers/m^2 to 1,85 pers/m^2. The maximum density and flow observed is 1,85 pers/m^2 and 71 pers/m*min which is Level E according to the Level-of-Service standards.

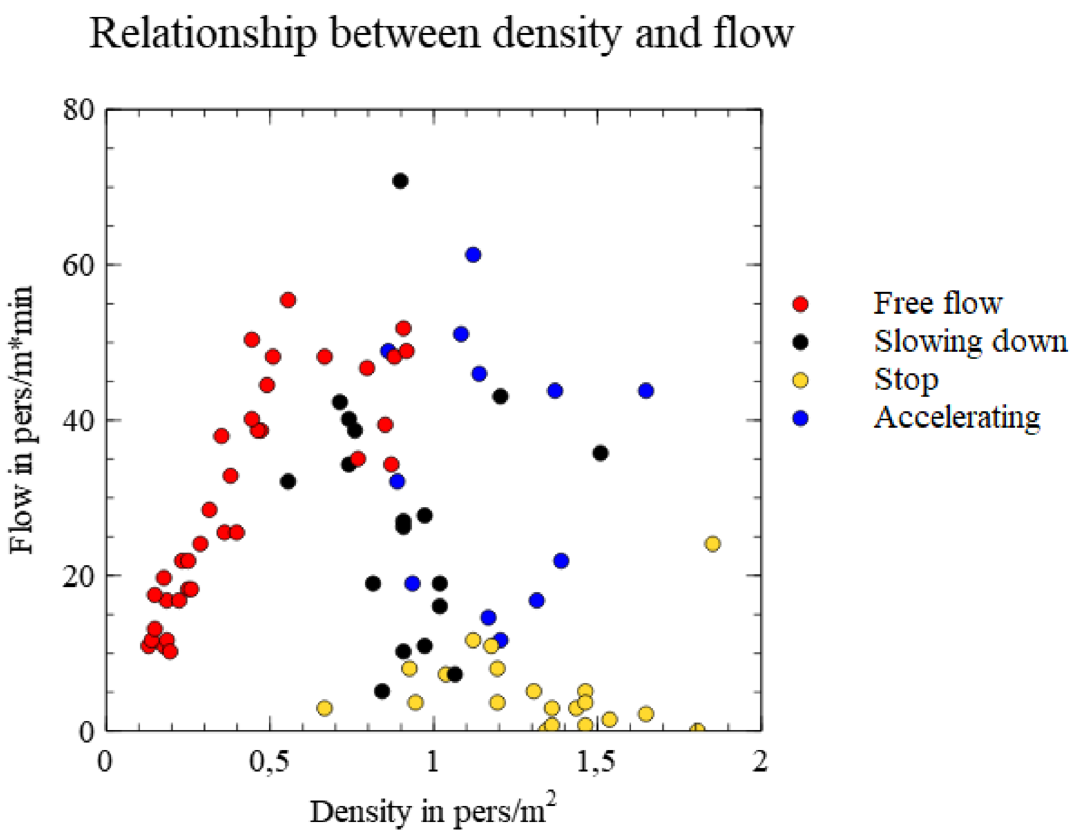

Figure 14. Diagram of the relationship between density and type of flow.

In Figure 15 below the relationship between density, flow and time of day is presented with a diagram. In this graph the flows are not categorised, to simplify interpretation. In the beginning of the analysis which is also the beginning of the egress, both the density and flow are low. As the egress proceeds the density and flow rise to reach a maximum flow of 71 pers/m*min with a density of 0,9 pers/m^2. After approximately 30 minutes of analysing, the Stop-and-Go system is used, and the flow decreases while the density increases. The flow goes down to 0 and the maximum density during the stop is 1,85 pers/m^2. People are then allowed to walk again, and the density decreases while the flow increases. Another stop then occurs which again rises the density and lowers the flow down to 0. When people are allowed to walk again the density once again decreases while the flow increases.

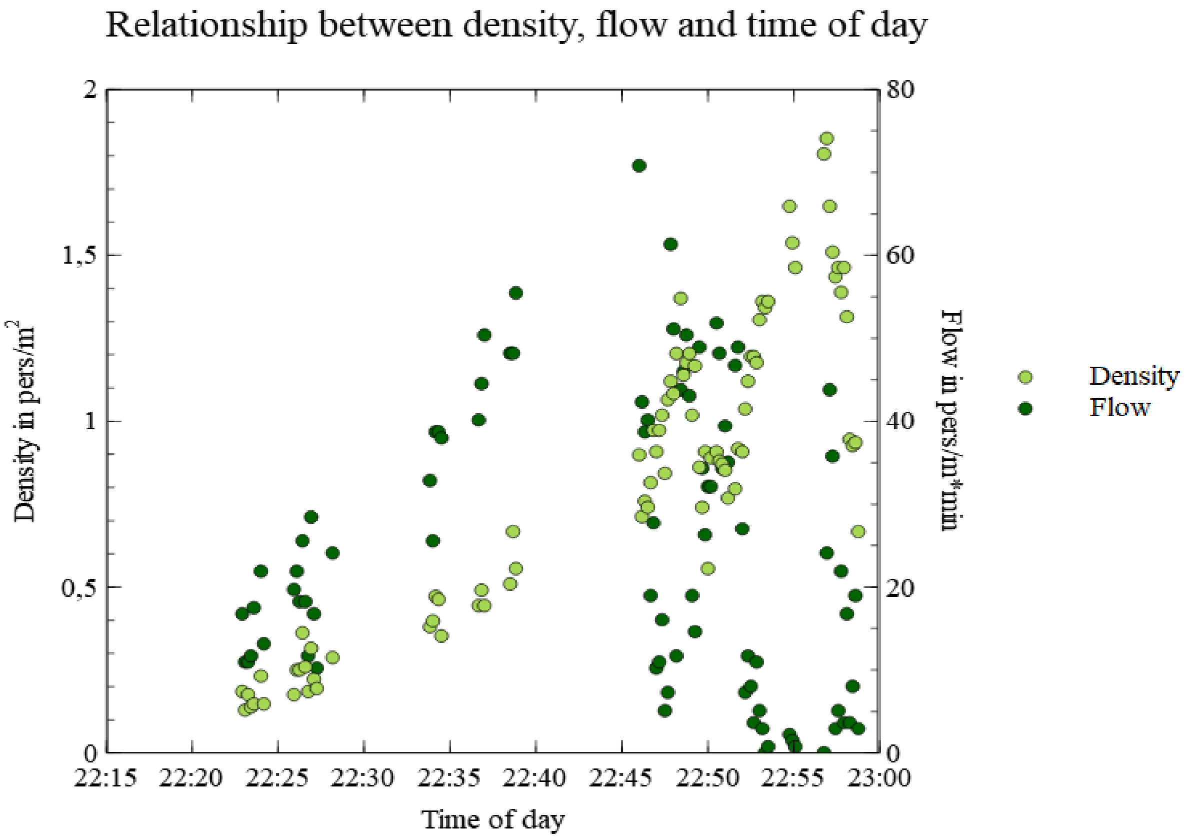

Figure 15. Diagram of the relationship between density, flow and time of day.

5.4 Concert with female pop singer

This event was a concert of a world known female pop-singer. The event took place during the summer and the concert ended late in the evening. The majority of the audience consisted of teenage girls walking in groups of two to five people. In some of the groups one parent was present which indicates that these girls would be in their early teens. Besides teenage girls, the audience mostly consisted of young couples. A behaviour that frequently could be observed in this crowd was people holding hands and walking near each other in groups or couples, despite this the flow of people was free during the whole egress. It can also be seen in the videos that parents are waiting at the end of the ramp for their children to come out of the stadium. Due to the season, most people were wearing summer clothes.

During this event the Stop-and-Go system did not need to be used and because of this the flow was free during the whole egress. Figure 16 shows a diagram where the relationship between the density and flow during egress is presented. From the diagram it can be seen that the datapoints almost form a linear relationship between the density and flow, where the flow increases as the density gets higher. For this event the maximum density reaches 0,77 pers/m² and the maximum flow is 57,7 pers/m*min, which represents Level D on the Level-of - Service scale.

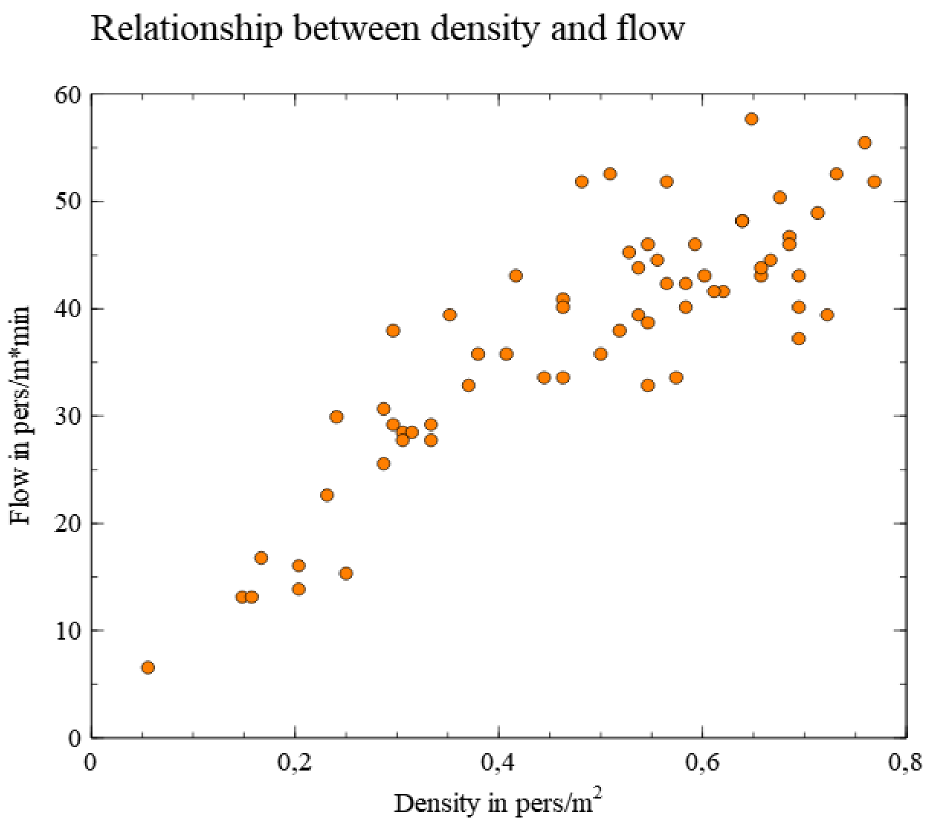

Figure 16. Diagram of the relationship between density and flow.

In Figure 17 the relationship between the density, flow and time of the day for the event is presented which enables a view of how the density and flow change over time. It can be seen that both the flow and density increase as the egress proceeds. During the first 20 minutes of egress, both the density and flow increase and then reach their maximum value before they then slowly start to decline until the egress is finished.

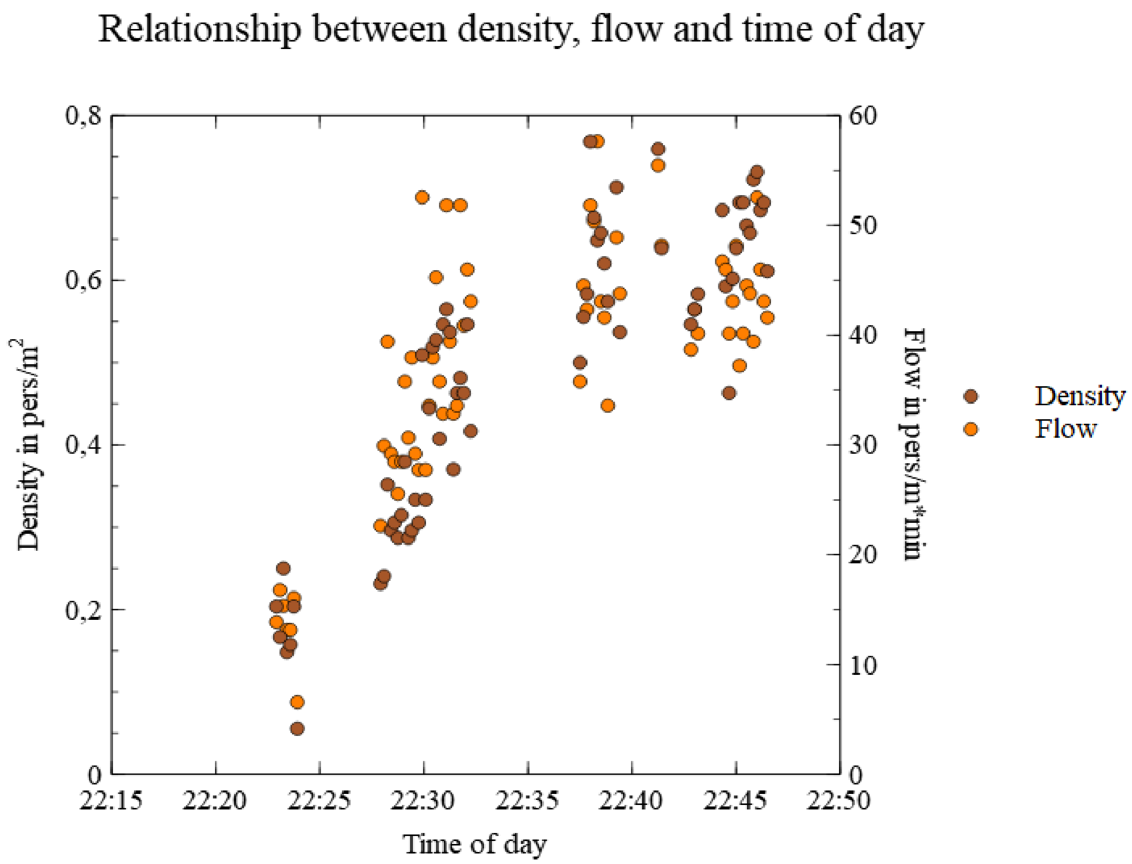

Figure 17. Diagram of the relationship between density, flow and time of day.

5.5 Comparison

In the following section a comparison of the four events density and flow relationships and the density and velocity relationships will be made to be able to see what differences there are. For the two events where the Stop-and-Go system was used, a separate comparison will be made including all types of flow to be able to compare this with the values recommended in the regulations.

In Figure 18 below the relationship between density and flow for all four events during free flow is presented; i.e. when no procedural attempt was made to manage the flow. Each event is presented with different colours, which can be seen in the label of the graph. From the diagram it can be seen that density and flow are reasonably similar for all events until the density reaches a value of 0,5 pers/m^2. It can also be seen that the rugby game is the event with the lowest density and flow while the concert with the female pop singer has the highest flow. The two events where the Stop-and-Go system is used (football and male singer/songwriter) have the highest densities where the flow is a bit higher for the male singer/songwriter at the top densities.

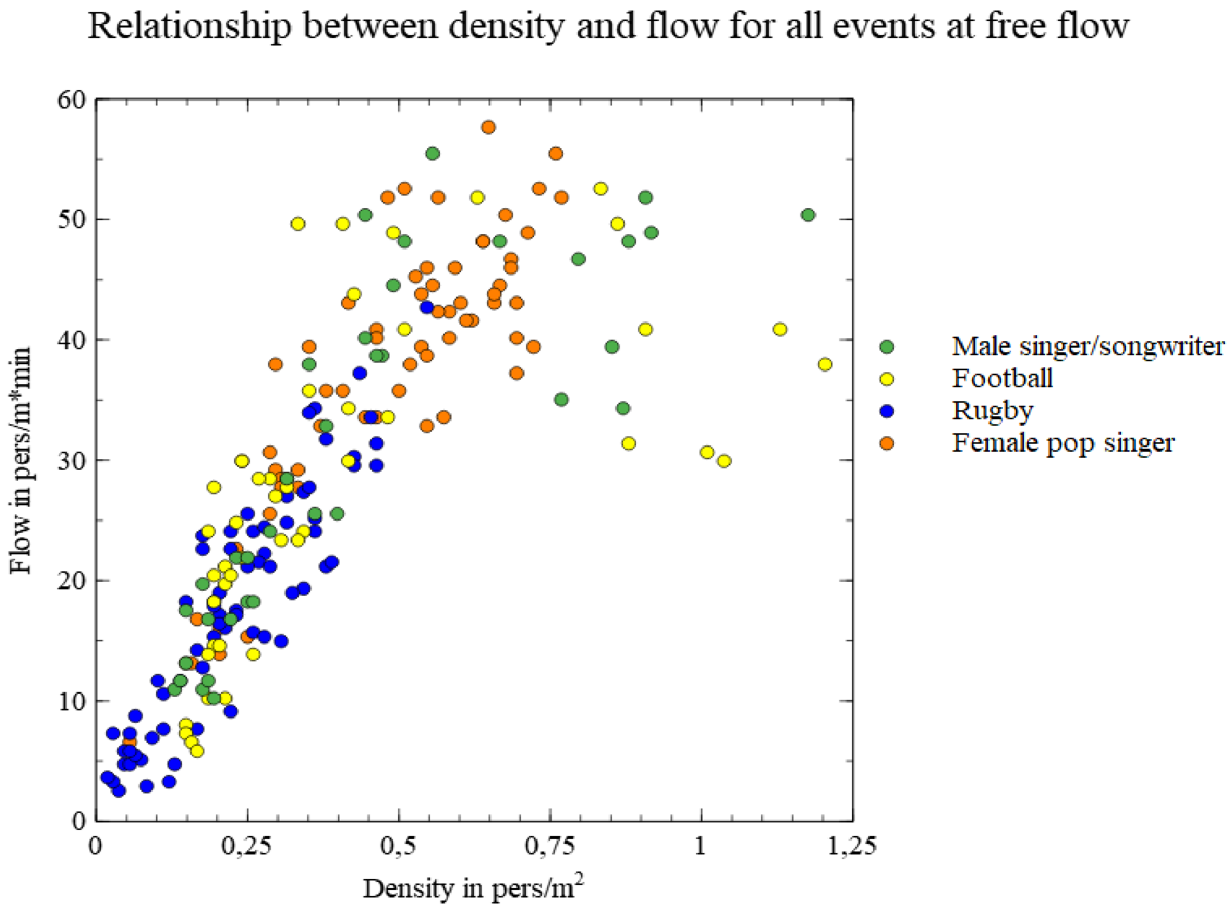

Figure 18. Diagram of the relationship between density and flow for all four events at free flow.

In Figure 19 below the relationships between density and flow during free flow for all events is presented with power trendlines. The equations for the different trendlines and their R^2 values are presented in Table 1.

Table 1. Table showing the equations for the different trendlines in Figure 19 and their R^2 values.

Event	Equation	R^2 value
Football	$y=51{,}495x^{0{,}6923}$	0,5429
Male singer/songwriter	$y=57{,}941x^{0{,}7509}$	0,7999
Female pop singer	$y=65{,}596x^{0{,}764}$	0,8516
Rugby	$y=59{,}9x^{0{,}808}$	0,7867

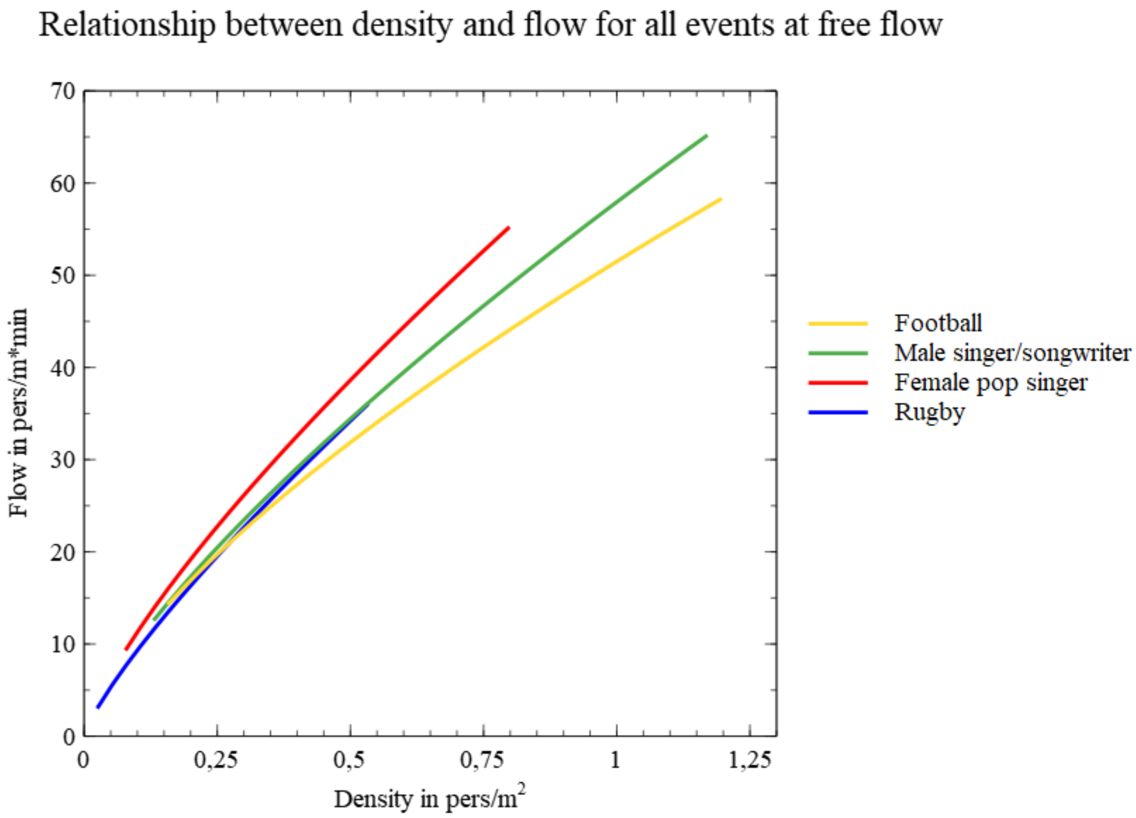

Figure 19. Diagram of the power trendlines showing the relationship between density and flow for all four events at free flow.

In Figure 20 the relationship between density and type of flow for the football game and the concert with the male singer/songwriter is presented. These are the two events where the Stop-and-Go system is used. When it is free flow, both of the events have a similar relationship between the density and flow. During the football game it can be seen from the diagram that when the crowd slows down the flow gets quite low but for the concert the flow is much higher even though the crowd is slowing down. When the stop occurs the density at the concert gets higher than at the football game in some cases and in others, the density is lower at the concert during the stop. When the spectators accelerate at both events the relationship between density and flow looks quite similar.

Relationship between density and type of flow for football and male singer/songwriter

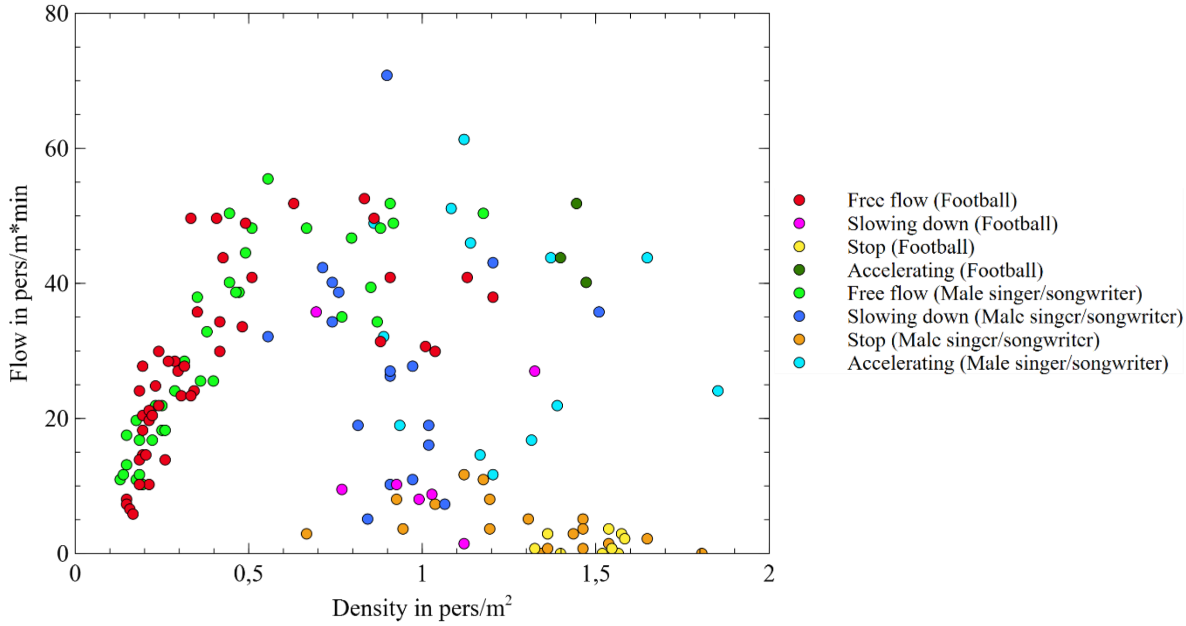

Figure 20. Diagram of the relationship between density and type of flow for the two events: football and male singer/songwriter.

In Figure 21 below the relationships between density and velocity of the spectators for all four events and for all types of flows are presented. In the diagram it can be seen that for low densities the walking speed is lower for the rugby game than for the other three events. The two events with the highest densities (football and male singer/songwriter), which also are the two events where the Stop-and-Go system is used, are the ones that have the lowest walking speeds with a minimum value just below 0,5 m/s. For the other two events the velocity never decreases below 1,2 m/s. All four events have a maximum velocity of 2,3 m/s.

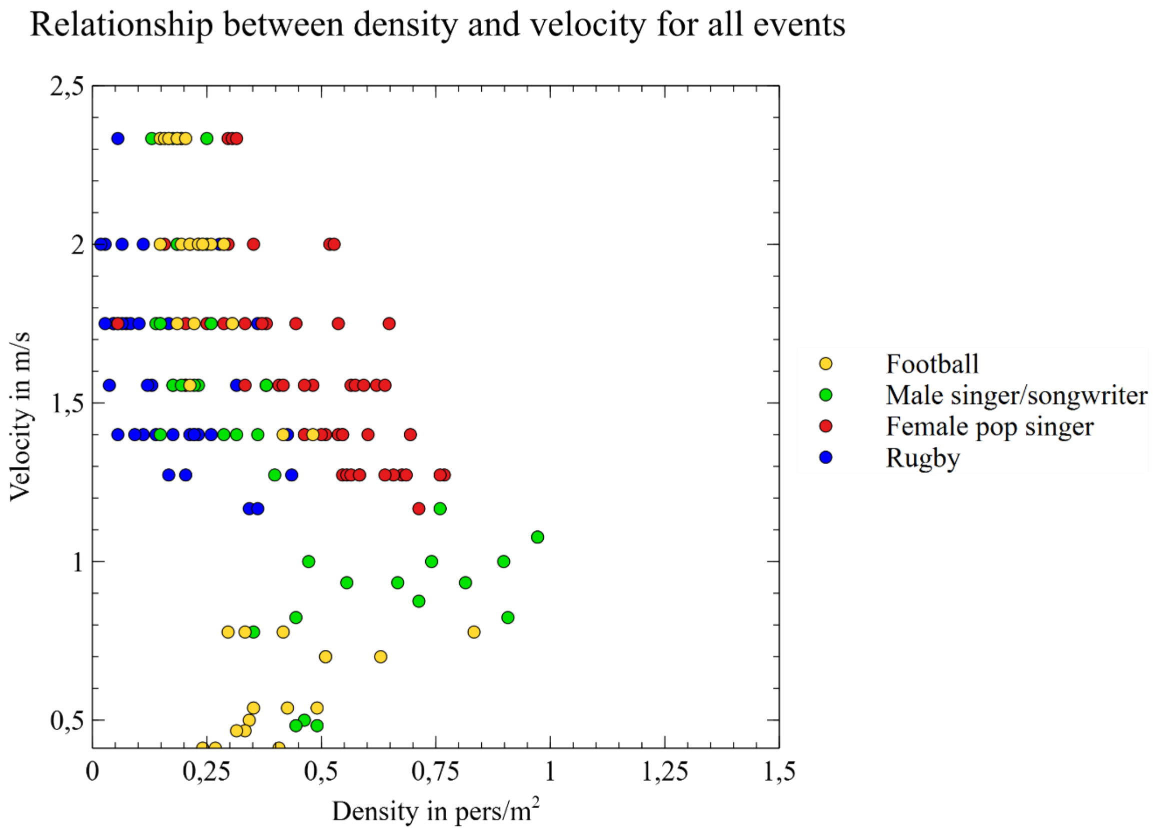

Figure 21. Diagram of the relationship between the density and velocity for all four events.

In Figure 22 below the relationships between density and velocity of the spectators for all four events are presented with polynomial trendlines. The equations for the different trendlines and their R^2 are presented in Table 2. For the football game the velocity first decreases and then levels out when the density is higher than 1,2 pers/m^2. For the other three events the velocity decreases linearly when the density increases. When the density is lower than 0,4 pers/m^2 the spectators from the football game have the highest velocity. However, the velocity for this event decreases fast and for higher densities the spectators from both of the concerts have a higher walking speed.

Table 2. Table showing the equations for the different trendlines in Figure 22 and their R^2 values.

Event	Equation	R^2 value
Football	$y=0,9925x^2-3,0927x+2,8026$	0,8706
Male singer/songwriter	$y=0,2643x^2-1,7388x+2,2757$	0,8133
Female pop singer	$y=-0,3845x^2-0,8844x+2,1751$	0,4875
Rugby	$y=-0,3301x^2-1,0384x+1,8458$	0,3083

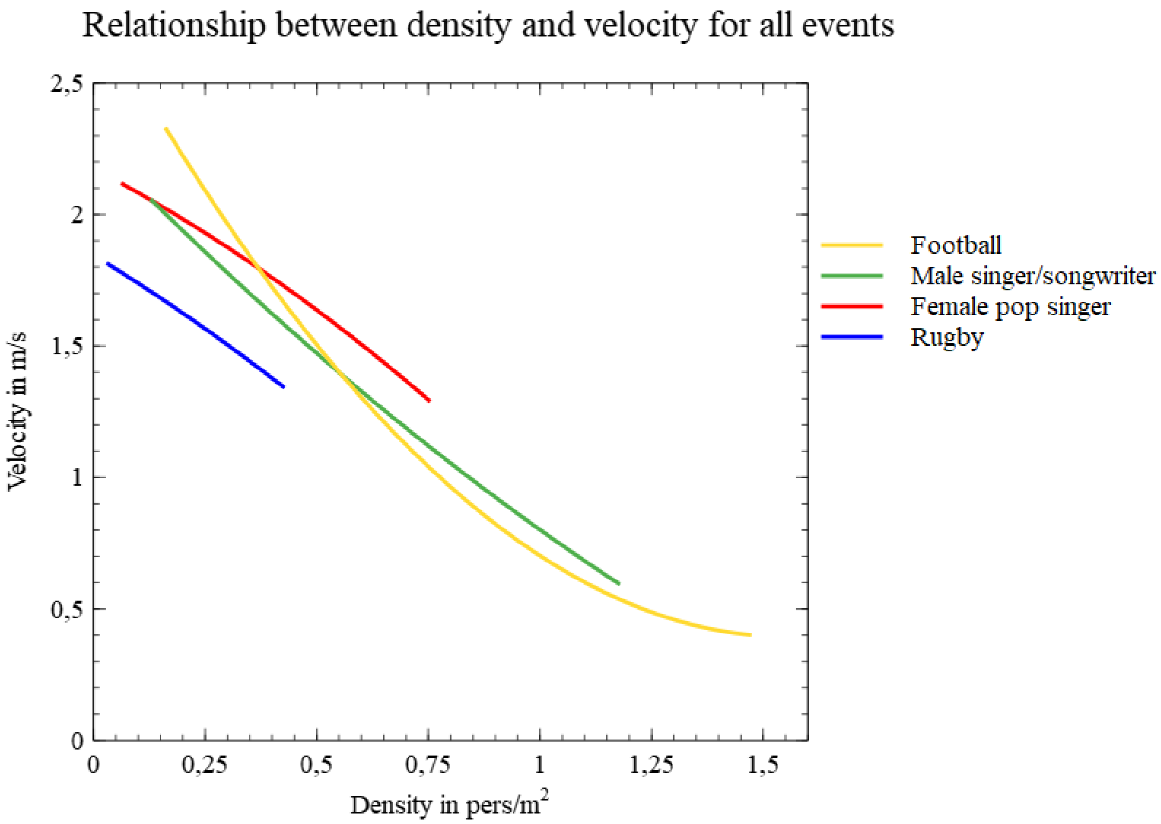

Figure 22. Diagram of the polynomial trendlines showing the relationship between density and velocity for all four events.

6. Discussion

The results from the analysis show that the density never exceeds the optimum density of 2,0 persons per square metre that is recommended in the Green Guide for general concourse areas. Also, the flow is lower than the recommended maximum flow rate of 82 persons per meter width per minute. However, in this thesis only four events have been analysed and it is possible that for other events the densities and flows reach higher values. When comparing the results of this analysis with Fruin´s Level-of-Service (Fruin 1971a), the events all range between level C to E at their maximum density.

When comparing the trendlines for the relationship between density and flow at free flow the trendline for the concert with the female pop singer is the steepest and the trendline for the football is the least steep. One possible reason why the female pop singer has the steepest trendline could be because of the crowd which mostly consisted of young teenage girls. Since teenage girls in most cases have a smaller body area than an average adult male, they have more space per person which allows them to walk faster, as could be seen in the results. Because of the higher walking speed and the low density, the flow can be higher than for the other events. In the Japanese experiment conducted by Fujii et al. flows as high as 155,5 pers/m*min was observed which is much higher than the recommended maximum flow rate of 82 pers/m*min in the Guide to Safety at Sport Grounds. The high flow might depend on the smaller body size of the Japanese people in comparison to Europeans. This could also explain why the teenage girls has the highest flow. Another factor that may have caused the higher flow in the Japanese experiment could be cultural differences between European and Asian people. Regarding the football game, one reason that the curve is the least steep could be due to the fact that this event occurred during the winter, hence people are wearing bulkier winter clothes and take up more space (Predtechensky & Milinskii 1978). It was also observed that the spectators at this event kept more distance to each other. This means that fewer people can pass the line out from the control area at the same time which gives a lower flow.

The highest densities that occurred during the four events were at the ones were the Stop-and-Go system was used (football, male singer/songwriter). The maximum density observed for all events was at the concert with the male singer/songwriter, during a stop. However, this density is still below the maximum value recommended in the Guide to Safety at Sport Grounds. As mentioned in the results, the spectators at this event were mostly couples or smaller groups of friends who walked closely together. The event took place during the summer and people were wearing thin summer clothes, which makes them take up a smaller area in comparison to the spectators at the football game. Because of this, during a stop, spectators at the concert can comfortably stand closer to each other which gives a higher density. It was also observed that at the football game, where the crowd consisted mostly of men, the spectators seemed to want to keep more distance to each other. As mentioned in the theory section men might be more prone to have an aggressive behaviour during large crowd events (Madensen & Eck 2008). However, this was not observed during this event. One factor that may cause aggressive behaviour is alcohol consumption and as mentioned earlier in the report it is possible to purchase alcohol at the stadium. Since we do not know how high the alcohol consumption was during the different events, we cannot tell if this had an impact on the spectator’s behaviour. Another factor that also may have had an impact on people’s behaviour during the egress from both of the sport events is the outcome of the games.

However, because we do not have any information about the results from the games we cannot say if this was a contributed factor to the calm behaviour that we observed.

At free flow the highest density can be observed for the spectators at the football game. A possible reason for this might be that most of the spectators at this event walk one by one while at the concert with the male singer/songwriter most of the people are holding hands. As mentioned in the theory chapter, humans' lateral spacing is determined by body sway and width of the human body (Fruin 1971b). Since the people at the football need less lateral space when they walk than the couples at the concert, they can be in a higher density and still walk comfortably.

The event with the lowest densities was the rugby game. However, the number of people passing through the control area seemed to be less than for the other three events. This event was also the one with the lowest walking speeds despite the low density. A possible explanation to why the walking speed was low is that during this event there were more elderly people and children present. The event also ended in the afternoon which can have contributed to the lower pace during the egress because people did not need to rush home. It was also observed that because of the low density and time of the day, people seemed more relaxed and walked in bigger groups talking to each other. At this event the flow of people was not unidirectional which might have affected the walking speed of the crowd leaving the stadium.

The densities observed in this analysis are much lower than the densities observed in for instance the field studies made during the Hajj pilgrimages (Löhner et al. 2017). However, the pilgrimages can be seen as a unique situation regarding crowd safety giving undesirable high densities. Also, the stadium is designed and has a capacity for a certain amount of people which is not exceeded during the events. In comparison to the experiment conducted in Düsseldorf, where the participants did enter a music event, the densities at the stadium are also much lower (Sieben, Schumann & Seyfried 2017). However, this was an arranged experiment where the participants were encouraged to act in a certain way, and it is therefore not comparable with the egress from the stadium. Furthermore, both the Hajj pilgrimages and the experiment in Düsseldorf were focused on the ingress while this thesis study only considers egress.

Considering the walking speed, the results show that during the lower densities the walking speed is over the values for average walking speed and for densities over 0,9 pers/m^2 the walking speed is under the values for average walking speed. This might depend on that the lowest densities occurs during the early egress. People who visits the stadium frequently knows about the Stop-and-Go system and want to avoid being delayed by the system. Therefore, they might try to hurry out from the stadium and walks faster than they usually do. One reason for the lower walking speed at the higher densities might be that there is less space for the people to move which makes it more difficult to walk in a normal pace. The low walking speeds all occur during the two events where the Stop-and-Go system was used. Because people are being stopped it might be difficult to estimate the relationship between density and walking speed right before and right after the stops. If the crowd had not been stopped, then the walking speed would have depended mostly on the density.

Regarding the graphs in Chapter 5.5 for comparison between the different events the R^2 values was used to determine which type of trendline to choose. These trendlines was only created to be able to compare the different crowds at the different events. It was not possible to find a type of trendline that had a perfect fit for all measuring points. Instead the type of trendline that had the best fit for the majority of the events was used. Because of this the trendlines does not reflect the exact results of the analyse and therefore they cannot be applied on other cases.

Throughout the analysis many assumptions have been made. Firstly, the quality of the videos and the angle of the camera have affected the counting of the people which affects the accuracy of the results. Three out of four events took place during the evening, which made the videos dark with a lower quality at higher densities, especially as most of the people were dressed in dark clothes. The angle and distance of the camera made it difficult to distinguish people at the back of the control area and shorter people where hidden behind taller people. Due to these factors it is likely that some people have been missed out during the counting for the densities and flows. These errors are estimated to be approximately 5-10 people for higher densities and approximately 1 person for the low densities. However, throughout the analyse, control countings of the density and flow has been done. As mentioned in Chapter 4, one person was counting the people while the other one kept track of the time, but at every tenth measuring point this person also did a control count of the people. Since the differences during the control countings was low this is assumed to have contributed to reduce the uncertainties regarding the density and flow.

When determining the velocity an assumption was made that the distance between the two lines were 14 metres, which was not a calculated value. This error is estimated to be approximately 1 metre. When selecting the individuals who were tracked through the control area, people who walked a similar path were chosen to be able to use the assumed distance. Due to the estimated distance, the actual velocity may differ from the calculated value. However, the values for the walking speed does not differ much from the values for average walking speed, which is 0,8-1,7 m/s, and is considered to be reasonable. Because of this, the estimated errors are considered to be acceptable and should not have affected the results too much. Since the control area is located below a ramp this might have affected the walking speed of the people entering the area. However, the inclination of the ramp is unknown which makes it difficult to estimate how much this might have affected the results.

The analysis method used was chosen because of the large area inside the control area and the factors mentioned above. An alternative method that could have been used is to count the people walking in to and out of the control area, giving a flow both in and out and from this derive the density. This would have given a density and flow relationship over time instead of at certain times. The reason why this method was not used is that in three of the videos it was not possible to see the people crossing the line at the back of the control area, and at the fourth event the flow was not unidirectional. It would also have been preferable to have a smaller control area as this would have made it easier to analyse the data, but due to the lack of reference points on the ground at the end of the ramp, it was not possible to make the area smaller. Because of the large control area, the calculated densities are an average value for the whole area and the local densities within the area might have been higher at certain times. The size of the control area has also affected the determination of the different types of flows. For example, during the Stop-and-Go, people in the back of the control area still walked when the people in the front had stopped, making it hard to determine which type of flow the majority of the people had.

7. Conclusions

In this study, different crowds egressing from a sport stadium have been compared regarding density, flow and walking speed. Also, the behaviour and demographics of the crowds have been reported. The results show that the densities of the crowds never reached the maximum density of Fruin´s Level-of-Service. Furthermore, the density and flow never exceed the maximum values for density and flow recommended in the “Green Guide”. However, it has been found that the demographics of the spectators along with external factors have an impact on the density, flow and walking speed observed. The observations and the results from the analysis show that:

- Male spectators tend to keep more distance to each other than for instance women and couples.
- Based on one of the most used definitions of people density (i.e. number of persons per square metre), the season of the year has an impact on the density as regards the amount of space each person occupies depending on what clothes they are wearing.
- In this study the walking speed depended more on the type of crowd than the density, for example, the event with the lowest density also had the slowest walkers.
- The area of the body has an impact on the density and flow relationship, where smaller spectators have a higher flow during higher densities compared to larger spectators at the same density.

At this specific stadium the density never reaches any levels above 1,85 persons/m^2 during the four observed events. However, the literature study shows that substantially higher values do occur which calls for further research within the field.

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