



The impact of crowd composition on egress performance

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ABSTRACT

The data that is currently used when designing egress systems for stadia and other high-occupancy buildings was collected decades ago and might not be applicable in today's society. A systematic analysis of crowd movement was performed to investigate egress flows at a large stadium in the UK following four different event types (i.e., a football game, a rugby game, a concert featuring a male singer/songwriter and a concert featuring a female pop artist). Video footage captured the egressing crowds and the relationships between velocities, flows and densities across the different events were established. The results indicate that the crowd composition, along with external factors (e.g., weather), have a measurable impact on the velocities, flows and densities observed. These differences are likely linked to the body area occupied by different crowds and the social interaction between members of the crowd. The observed flowrates were all below 60 people/m²min, which is significantly lower than the maximum value (82 people/m²min) recommended in the 2018 Guide to Safety at Sports Grounds (the sixth edition of the "Green Guide"). The observed behaviour and flowrates suggest the need to carefully consider the impact of crowd composition when planning stadium egress including emergency evacuation.

1. Introduction

When designing and managing crowded places (such as stadia, arenas, festivals, urban centres and transport hubs), there is a need to demonstrate sufficient levels of safety and security for people arriving, circulating and egressing through the space. Plans must take into account the pedestrian movement dynamics in and around the space. This is typically represented using "flowrates"; i.e. measures of people over time, at arrival, circulation and egress [1] along with their relationship with other key variables in pedestrian planning (e.g. velocity and density [2–5]). Plans must also detail evacuation procedures to demonstrate that crowds can be moved to a place of (relative) safety within an acceptable timeframe (as determined by risk assessment of likely threats, including fire, natural disasters, attack scenarios, etc.).

For those designing these systems of crowd movement in new sites (or planning and refining operations in existing places), it is crucial to have engineering tools (data and methods) that are contemporary. This is needed to ensure that the analysis of pedestrian and evacuation movement is representative of the crowd, allowing planners to assess performance and avoid undesirable conditions, such as extreme crowding. Unfortunately, the engineering tools used today to assess pedestrian movement are based on data collected decades ago,

undermining their representativeness of the modern crowd. Seminal work conducted by Pauls [6,7], Fruin [8], and Predtechenskii and Milinskii [9] is still the basis of many of the calculations currently used to assess pedestrian and evacuation movement. This is despite the original researchers withdrawing their data (and associated findings) from authoritative engineering handbooks [10], as it was considered out-of-date, given significant demographic changes over the last few decades. Most western societies have aged (leading to higher proportions of the population being subject to movement impairments and declining health) [11] and have higher obesity rates (affecting individual footprints, attainable velocities and fatigue levels) [12]. The crowds we expect at sporting and music events are more diverse than ever before, for example there are a higher proportion of women and children in the modern crowd, which might not be reflected in the seminal data which focused on dynamics of crowds consisting primarily of adult male pedestrians. In addition, the most credible data-sets were collected prior to the introduction of mobile technologies that are now prevalent and which might affect individual velocities and local navigation.

The design of stadia in the UK is highly influenced by the Guide to Safety at Sport Grounds, also called "the Green Guide" [13]. The Green Guide helps sports grounds owners and operators calculate safe capacity for their venue. Although it is primarily used to provide a benchmark for

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safety certification in the UK, it is also used internationally by architects and event planners as a best practice guide for the development, refurbishment and planning of stadia, arenas and events. The guide is considered a 'go-to' document for planning safe capacity, and the recommended flowrates in the guide are widely applied to calculate the size (width) required for crowd movement. When calculating the capacity for an exit route on a level surface, the recommended maximum flowrate in the guide is 82 persons per metre width per minute (ppmm) and 66 ppmm on a stepped surface. It is emphasised that more comfortable circulation conditions can be achieved by considering flowrates below 82ppmm, and the guide cites several factors that can affect these flowrates, such as: the gender and age of the spectators, the presence of children, toilet locations, stairways, weather conditions, the availability of alcohol, and the outcome of the event. Furthermore, it is recommended that the average crowd density should be no more than 2.0 pers/m² in general concourse areas. The recommended maximum crowd density for standing spectators and people queuing is 4.0 pers/m². 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 [13].

It is of vital importance to evaluate if the values and methods provided in the Green Guide are suitable for current populations. In fact, the near-ubiquitous use of these flowrates for planning large crowds is at odds with the latest methods in adjacent fields (e.g. evacuation calculations in Fire Safety Engineering [14]), in which standard calculations do not recommend a single flowrate but rather a flowrate that is considered in proportion to the density of a population [15]. This is because, when interacting with other pedestrians (e.g. when walking in a crowd), people tend to adjust their velocity and manoeuvre to maintain a distance between themselves and others (e.g. proximity to familiar others and distance to others) and to avoid physical obstacles [16]. As spaces become more congested and distances between people reduce, it becomes more challenging for people to maintain sufficient distance between each other to ensure free movement – for them to manoeuvre and adopt a velocity in the chosen manner. It has been established that the population density (the inverse of distance between people) affects achievable velocities and the flow levels that might subsequently be produced. The number of individuals co-located in a space affects the separation distances between people, the individuals' achieved velocities and then the crowd flow as a whole. The collective behaviour and collective flowrates of a crowd emerges from the interactions between an individual and the people in their immediate surroundings, where each individual is influenced by multiple neighbours [16–18]. This interaction is affected both by the physical and social parameters mentioned above.

To support egress planning, there is a need to better understand the achievable velocities and flowrates in large crowds. Examining this in an experimental setting can be difficult because of resource limitations (e.g. space and population), ethical concerns (e.g. producing representative conditions without endangering the participant population) and issues with ecological validity (i.e. participants know that they are in an experimental setting and therefore do not perform as they would in a real setting). Given these issues, we instead decided to observe data from real events. This reduces our control over the conditions faced, but provides access to large numbers of people performing credibly given the conditions faced.

The aim of this research is to add to and update our understanding of large crowd flow during different sports and concert events, by providing modern data and evidence. This article presents data analysed from video sources during egress at four different sporting and music events at a large stadium in the UK in 2017 and 2018. The video focused on one (deliberately selected) location to allow direct comparison. Specifically, the case study includes egress movement on a ramp outside a large stadium (i.e. no vertical egress within the stadium was observed). Flow, velocity and density indicators were collected across the events,

enabling an examination of the impact of the different demographic profiles evident at the different events. Both free flow and stop-and-go conditions were observed. The objective of this analysis is to compare pedestrian movement for different crowd compositions and subsequently different event types. Analysis of video footage of the primary egress route during each event is used to investigate:

- Flow versus density conditions.
- Velocity versus density conditions.
- Differences between sport spectators and concert goers.
- Other behavioural factors identified that further characterised the four events.

The data-sets provide a useful addition and update to the current understanding, and the comparison of pedestrian movement at different events may introduce a new element that needs to be considered in engineering analysis and that is often overlooked; i.e. the cultural, social and demographic impact of the event itself on performance. There is a wide industry need for this type of research to continue and develop our understanding further, to help improve measures of comfort and safety at stadia and other infrastructures hosting large crowds across the world. In particular, findings from this article, and ongoing research at similar sites, might have implications for future guidance and regulations given the current reliance upon flowrates derived from authoritative field and experimental work.

There are a number of challenges posed by the data currently available [6]: as mentioned, it is not representative of current performance; original conditions are not reflected in current applications; data format types used are not reflective of current needs (for instance, of contemporary modelling tools); the data is collected and therefore more applicable for one sector or domain (e.g. research); most importantly, the data is not sufficiently documented to enhance transparency and enhance credible, responsible use.

The work here has deliberately attempted to address these issues by incorporating researchers, model developers/users, and practitioners in the project team; ensured that the data collected provides research insights and is model ready; is collected at the component/sub-population level rather than the structure level more easily allowing wider use; and is documented according to current best practice [6].

2. Source material

The facility under consideration is a large stadium in the UK (it can host over 70,000 seated people during sports events and over 10,000 standing during concerts) used for various events, such as football games, rugby games and music concerts. Stadia such as this have seen an increase in these "alternative uses" from sports events, with changes in the music industry increasing the demand for stadium-sized tours, at which it is possible to purchase food and alcohol. A camera survey was conducted throughout the stadium site, across four different types of events. This enabled video analysis of the same locations around the site, under different crowd conditions.

3. Methodology

Crowd egress data-sets were collected through video recordings performed at the stadium under consideration. The video footage used in this work is obtained from one of the several cameras placed at different locations around the whole stadium and was selected as it represents the primary egress route from the stadium (i.e. experiences the largest crowds on a typical egress).

For the safety of the spectators the stadium safety management and transport operators adopt a Stop-and-Go system during egress at high-capacity events. This system is used in many large crowd environments to reduce waiting densities. When the crowd managers/stewards assess that the queue have reached a specified point at the end of the

horizontal walkway, people at the beginning (i.e., below the ramps) are stopped and then released. There are several positions in this stopping system, enabling crowd management positioning at regular intervals on the egress route. For two of the events that have been analysed here, the Stop-and-Go system was used.

3.1. Measurement location

Footage of the egress from the stadium was recorded during several events on different dates during 2017 and 2018. As a first step, a visit to the stadium was arranged to decide which of the camera footage to use and which events should be analysed in order to obtain a representative group of different crowd compositions.

During an egress scenario in the stadium, there are several different walkways to flow out. The camera recordings facing the most used egress route was selected. This camera was deliberately located at the front-end of the structure and it had a clear view of a relatively large area (see Fig. 1a for a schematic representation of the camera view). The arrows in Fig. 1 represent the movement direction of people (where the arrow in the centre represents the direction of movement in the ramp). The red lines in Fig. 1a represent the lines used for the measurement of the area in which pedestrian movement were observed. The green lines in Fig. 1c represent the elevated grid used to obtain information on pedestrian movement. The space recorded was also free from obstacles which enabled people to potentially walk freely – at least until density conditions dictated otherwise - without interacting with obstacles. This means that their movement was impacted only by the space available on the ramps and the presence of people around them. This route consisted of two straight ramps leading down from the stadium to a horizontal wide walkway where most people choose to continue straight forward during egress (see Fig. 1a). People coming out from other exits could merge with the crowd coming down by the ramps when they reached the bottom of the ramps. This increased the number of people walking along the horizontal walkway. From examinations of all video footage, it was possible to identify that the ramps are used by approximately 30–50% of the visitors during egress, potentially meaning a demand in the region of 30,000 people during large events.

A control volume was identified based on a set of physical landmarks/reference points which could be identified in real life and in the camera recordings. This allowed to measure the dimensions of the lines of the projected area of the control volume and then estimate its size (see red lines in Fig. 1a). The projected area of the control volume was determined by splitting it up in two triangles. Their areas were then calculated by using Heron's formula and then summed and it was then determined to be approximately equal to 108 m².

3.2. Data analysis

Video footage from the selected camera recordings was analysed to investigate crowd egress movement. The software Kinovea™ was used to analyse the data. The software is a video player developed for people

movement analysis in sport, including features like moving along video frames and draw on top of the video images [19]. When determining the densities over time at the different events, the control volume has been drawn in the videos using a perspective grid. The grid has been laid out in the videos to match the control volume by using landmarks that can easily be seen in the video recordings. It has then been elevated to make it possible to count the people located inside the control volume (see Fig. 1c). The elevation is necessary to cover the people located at the foot of the ramp and on the right side along Line 2 in Fig. 1a. A systematic analysis of people location in the videos was used as reference to determine the height of the elevation, making sure that everyone located inside of the actual control volume was also covered by the grid. The number of people inside the control volume has then been determined by counting the number of heads seen inside of the lines of the elevated grid.

The procedure to determine the density and the flow was the same for all four events. When the elevated grid was laid out, the video was played from the start of the egress. The video was then been paused approximately every 10 centi-seconds and the number of people inside the control volume manually counted by a researcher. The numbers were then been entered into a spreadsheet where the density was calculated by dividing the number of people by the projected area of the control volume (108 m²). In reality, the population density would have not been uniform across the space. However, we were measuring the impact of this density on flow and speed. It is suggested that the density variation was not significant (confirmed through observation) given the relatively small area examined, the absence of physical differences/distractions within this space, and that the pedestrians traversing the space would have been affected by the densities at their current and projected locations – somewhat smoothing out the impact of any variation present. The control volume was sized to maximise the consistency of conditions while minimising the number of people traversing the space but not counted.

To reduce uncertainties in data analysis, flow-rates were also double checked by playing the video for 10 s and checking the number of people leaving the control area over the grid-line located closest to the camera (grid-line over Line 3 in Fig. 1a). These numbers, including the start and stop time for every data-point, have also been entered into the spreadsheet. The flow has then been calculated by dividing the number of people passing the line divided the time multiplied the length of the line, thus obtaining the flowrates in people/m*s and people/m*min (as this is the unit of measure reported in the Green Guide [13]).

After densities and flowrates had been obtained, the velocities were determined in the same way for all four events identifying a relevant sample of people which could be accurately tracked in the video recordings (e.g., people wearing bright-coloured caps, etc.) at given flows/densities. The pedestrian velocities were determined by dividing the distance a person had walked by the transit time. Velocities were then recorded in m/s. The average distance between Line 1 and Line 3 (see Fig. 1) was estimated to be approximately 14 m. This value was used for the estimation of velocities (i.e., velocity estimations are affected by this

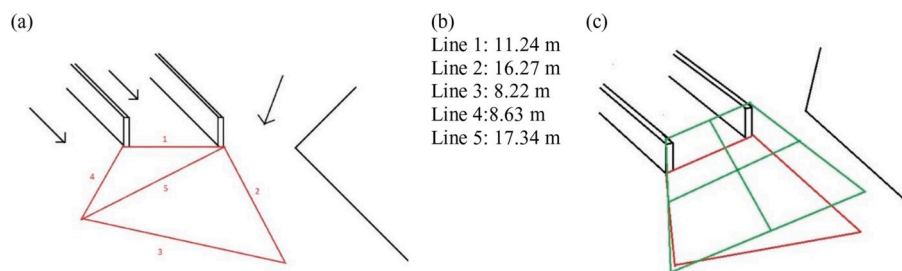


Fig. 1. (a): Schematic representation showing the bottom of the ramp and the beginning of the horizontal walkway, along with the projection of the area used for crowd movement measurements. (b): Dimensions of the lines used to calculate the projected area of the control volume are reported on the right. (c): Sketch of elevated grid above the control volume.

Table 1
Summary of main findings of the four complete collected data-sets.

Event	Time of the year/day	Crowd composition and behaviour	Number of data-points and people in the measurement area	Measured Upper Boundary Conditions
Football game	Winter/Evening	Mostly men (young adults, to people in their fifties or sixties), kept a notable distance from each other.	Flow/Density: 65 Velocity: 38 Range of people in the measurement area: 16-171	Max density: 1.6 pers/m ² Max flow: 52.6 pers/m/min LoS E
Rugby game	Summer/afternoon	Large variety of people (young adults to elderly people), low density.	Flow/Density: 68 Velocity: 41 Range of people in the measurement area: 2-59	Max density: 0.55 pers/m ² Max flow: 42.5 pers/m/min LoS C
Concert: Male singer/songwriter	Summer/evening	Mostly couples, hand-holding, young adults to elderly people.	Flow/Density: 86 Velocity: 36 Range of people in the measurement area: 14-200	Max density: 1.85 pers/m ² Max flow: 70.8 pers/m/min LoS E
Concert: Female pop singer	Summer/evening	Teenage girls, parents, walked close together.	Flow/Density: 64 Velocity: 56 Range of people in the measurement area: 6-83	Max density: 0.77 pers/m ² Max flow: 57.7 pers/m/min LoS D

approximation). When selecting the individuals who were tracked throughout the control volume, people who walked a similar path were chosen to be able to use the assumed distance. Then the video was fast-forwarded to the start time for the first data-point where one person was identified and followed while walking through the control volume. The time when the person entered and left the grid was noted, giving the number of seconds needed to walk through the control volume. This procedure was then repeated for several data-points at different density levels for all events. The velocities referring to the control volume were then entered into a spreadsheet. Random re-counting was performed by another researcher to cross check the values. While reviewing the video footage, estimations of gender, age and behaviour of the crowds were also observed and noted for all four events.

3.3. Performance indicators

The values reported in the spreadsheet were used to derive graphs showing the relationships between density and flow and between density and velocity (these were generated using the software Veusz™ [20]). In addition, the annotation on crowd composition and behaviour were used to help examining the crowd movement observed during different events.

In two of the events under consideration (football and the singer/songwriter concert), the Stop-and-Go system had been used, which resulted in a different type of density and flow relationship than the events without during some periods of time. For the events where the Stop-and-Go system was used, the flows have been categorised into four categories: free flow, slowing down, stop and accelerating. Free flow was assumed when people walked without procedural intervention and it was observed an even flow inside the control volume. Slowing down was assumed when at least 50% of the people inside the control volume reduce their velocity. Stop was assumed when nearly all of the people (>95%) inside the control volume were standing still. Accelerating was assumed when at least 50% of the people inside the control volume have started to walk after the stop. Here we give summary insights into the complete data-sets (i.e. reflecting conditions that might be expected in such events), and then produce more detailed analysis of the free flow data (i.e. reflecting relationships that might typically be employed in engineering analysis where only the surrounding population constrain flow, rather than the procedure employed).

4. Results

The results of the video analysis are presented below. A summary of the main findings from the complete data-sets (i.e. all conditions including those generated during the Stop-Go procedure) are reported in Table 1.

Table 1 shows the time at which the data-sets were collected, the overall crowd composition and behaviour, the number of data points collected (along with the range of people observed in the measurement area during the observations), and the maximum density and flows observed, along with the corresponding Level of Service (LoS) derived from densities [8]. This provides insights into the boundary conditions that might be evident at these types of events – in terms of flowrates and population densities. It is apparent from Table 1 that the flowrates produced are below those typically assumed in UK guidance (e.g. 82 per/m²*min) and the population densities also fall below those UK design guidance (e.g. 2.0 pers/m² in concourse areas). The observed movement was in the area immediately surrounding the stadium (rather than inside the stadium itself). These findings might therefore have implications regarding performance levels/conditions that might be expected (and assumed) inside a stadium and outside of the stadium. Although not definitive, (a) the variability in the maximum levels reached across the four events and (b) the fact that these maximum levels in the adjacent area to the stadium fall below design guidance, suggest that a more flexible approach might need to be investigated.

4.1. Qualitative observations

A number of qualitative observations were made. A simple outline is presented in Columns 1–3 of Table 1. These observations are now described in more detail. It is apparent that there are a number of demographic, social and behavioural differences between the populations. It is hypothesized that these differences manifest themselves as physical conditions (e.g. the local densities produced and subsequent space available, footprints occupied by individuals/groups), perceived conditions (e.g. what is considered normal at such an event), objectives (e.g. consistency/variation in the motivation of crowd members), affiliative actions (e.g. the impact of group memberships on expected group cohesion), etc. These factors interact in complex ways. However, the discussion below examines how these might be compiled to characterise the different events examined.

The football game was between a British and a foreign team. It took place during a late evening in the winter; therefore, people were wearing winter clothes. The age distribution is estimated to have ranged mostly between young adults to people aged between 50 and 69 years of age. Most of the attendees were men, along with a few families with children and a small proportion of couples. Most attendees were either walking alone or in smaller groups of two to four people. Some parents were holding their children by their hand and families seemed to keep together in the crowd (see Fig. 2 and Table 1). Therefore, there were a large proportion of individuals and loosely affiliated (typically adult, male) groups. Given this, people were able to keep a distance from each other during the egress when they chose to do so (e.g. for social comfort and to avoid obstacles and congestion), which allowed them to move without any major conflicts and kept the flow laminar.

The rugby game was a final between a British team and a foreign team. The event took place at the end of the summer (people were wearing summer clothes) and the game ended in the afternoon. Attendees' age range is estimated between young adults to people aged between 60 and 79 years of age. 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 a greater number of couples and families with children present. Many of the couples were holding hands and most of the parents were holding the hands of their children (see Fig. 2 and Table 1). Therefore,

there was a smaller proportion of individuals than in the Football game, with a larger proportion of dyads and connected small family groups (who tended to remain together by travelling at the velocity of their slowest member). From a qualitative point of view, density levels did not reach the higher values (seen elsewhere) during this event; thus, there was typically enough space for everyone to walk freely and avoid conflicts which resulted in mostly free flow during egress. This provided more of an opportunity for people to move freely, which was somewhat counteracted in places by the presence of groups and the demographic range. This also allowed people to talk more easily to each other while walking and maintain group cohesion.

The concert with a worldwide known male singer/songwriter took place in the summer (thus people were wearing summer clothes) and it ended up in the evening. The audience consisted of both men and women and the estimated age ranged between young adults to elderly people (between 70 and 79 years), although a predominantly younger crowd. People mostly walked in couples holding hands or in larger groups of both women and men (see Fig. 2 and Table 1). No families/children could be seen in the videos and the distribution between genders seemed approximately equal. Observations showed that people typically had space around them. The relatively connected groups or dyads meant that people were 'bound' to the slowest moving person in that group; however, given the relatively young audience, this had a minimal impact on adopted velocities – the variability of speeds within groups was reduced given the relatively young and sociable crowd present.

The concert with a worldwide known female pop singer took place during the summer (thus people were wearing summer clothes) and it ended late in the evening. The majority of the audience consisted of teenage girls walking in groups of two to five people. A young audience without bulky clothing produced a smaller set of pedestrian footprints than in the other cases. In some of the groups one parent was present possibly indicating that these girls would be in their early teens. Besides teenage girls, the audience mostly consisted of young couples. There was a large number of tightly-knit groups; i.e. people were frequently observed holding hands and walking near each other in groups or couples (see Fig. 2 and Table 1). The movement of people was typically free during the whole egress – with more space around the connected groups of spectators. Parents were seen waiting at the end of the ramp for their

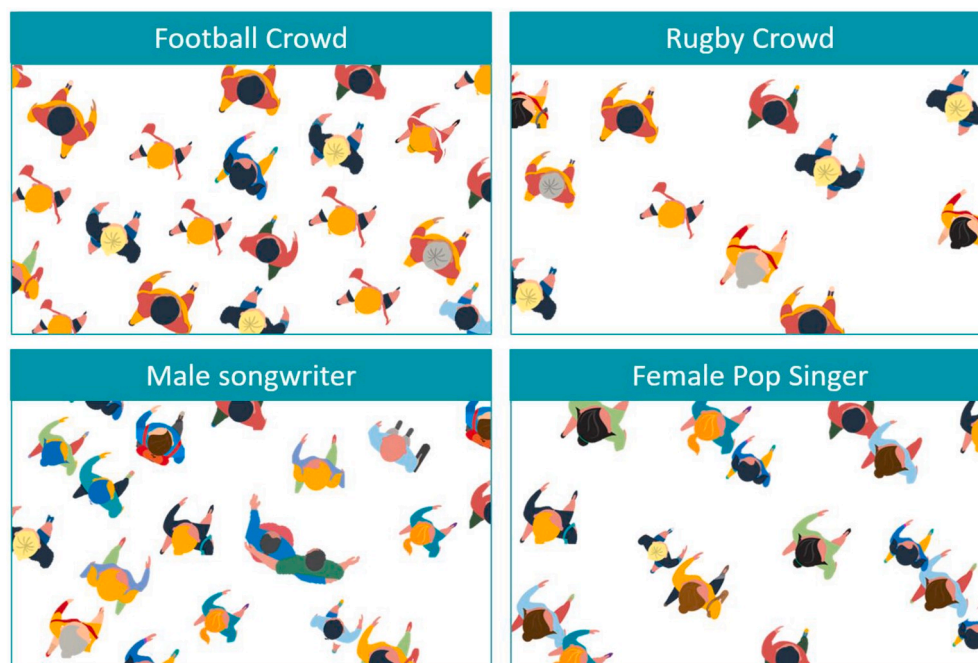


Fig. 2. Examples of crowd composition in the four events under consideration.

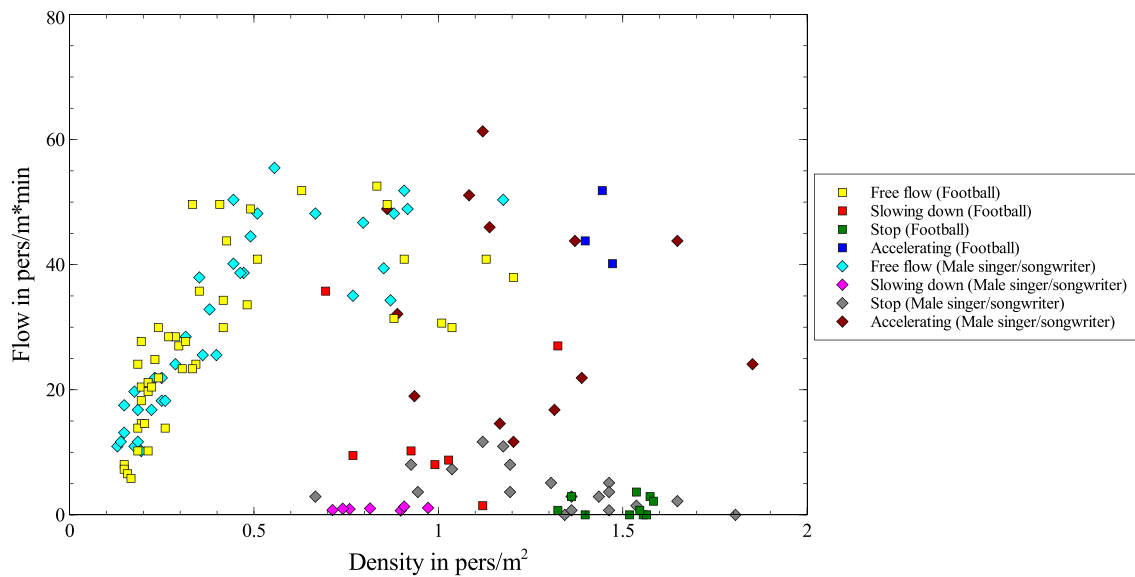


Fig. 3. Scatter plot of the relationship between density and flow for all four events in all conditions.

children to come out of the stadium.

4.2. Quantitative observations

Quantitative data were also generated from the video recordings. This includes density, velocity and flowrates estimations along with their relationships. These were generated for the overall data-set and for free-flow conditions and a sub-set of the data is reported below.

Fig. 3 presents the relationship between density and flow for all four events during all conditions; i.e. irrespective of the presence of the Stop-Go procedure. The highest achieved flowrate is 70.8 pers/m*min, produced during the Male Singer concert when spectators were being affected by the Stop-Go procedure. The highest density reached was 1.85 pers/m² during the Male Singer concert when spectators were being affected by the Stop-Go procedure (accelerating). It is apparent that at

densities lower than 0.5 pers/m² there is relatively little variation in the data involved (predominantly from football and male concert events), with an apparent relationship between achieved flow and density. Beyond a density of 0.5 pers/m², more flow conditions/event data are present producing greater variation in the results produced. The two events where the Stop-and-Go system is used (football and male concert) have the highest densities – suggesting why the Stop-and-Go procedure might have been adopted for such events in the first place. Two main observations can be made: the relationship follows a loosely correlated parabolic form; the events (and underlying conditions) do not have a consistent or continuous impact.

Fig. 4 presents the relationship between density and flow for all events during free flow conditions; i.e. removing the impact of the stop-and-go procedure on the results produced. It is therefore a sub-set of the data shown in Fig. 3. Fig. 4 shows that flow/density relationship is

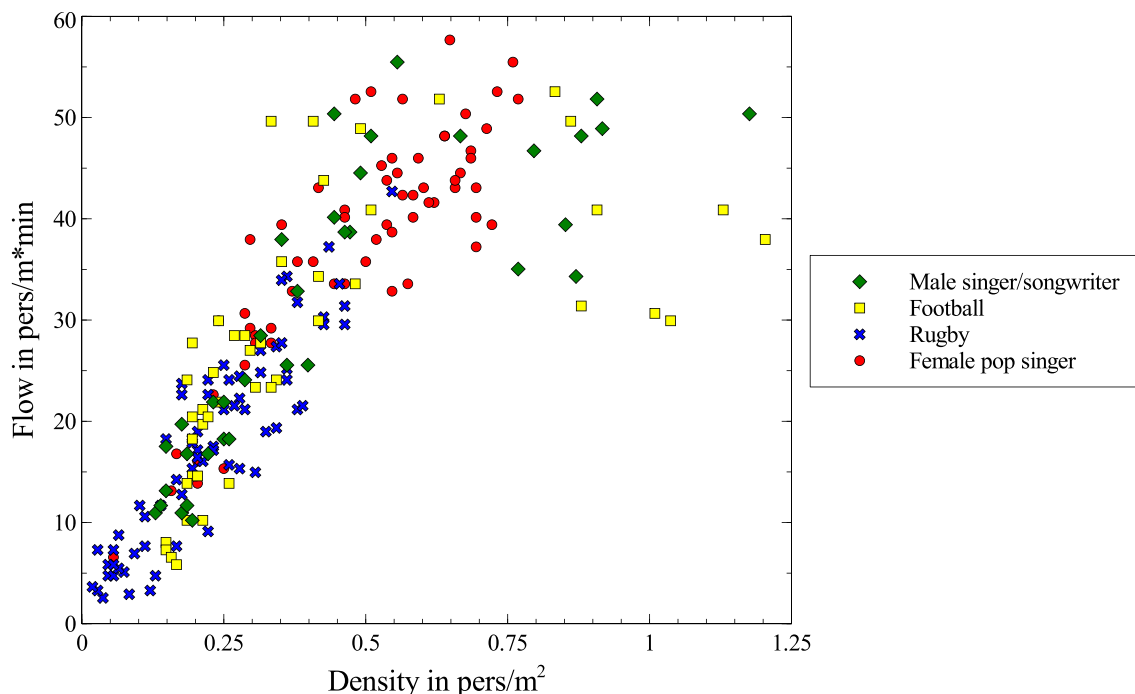


Fig. 4. Scatter plot of the relationship between density and flow for all events in free flow conditions.

Table 2
Descriptive summary of flow data from the four events (free-flow conditions).

Flow (p/m ² min)	Football	Concert: Male singer/songwriter	Rugby	Concert: Female pop singer
Min	5.8	10.2	2.6	6.6
Max	52.6	55.5	42.7	57.7
Average	27.7	30.9	17.8	37.4
St. dev	13.2	14.5	9.8	11.4

Density (pers/m ²)	Football	Concert: Male singer/songwriter	Rugby	Concert: Female pop singer
Min	0.15	0.13	0.02	0.05
Max	1.2	1.17	0.55	0.77
Average	0.41	0.44	0.23	0.48
St. dev	0.29	0.28	0.13	0.02

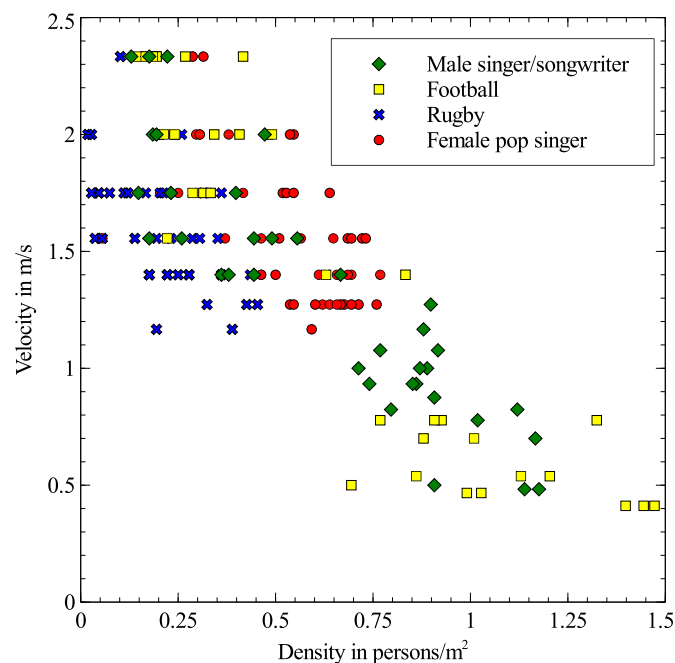


Fig. 5. Scatter plot of the relationship between the density and velocity for all four events including all data. Number of data points: Male songwriter/singer: 36, Football: 38, Rugby: 41, Female Pop Singer: 56.

relatively correlated until the density reaches 0.5 pers/m², after which there is more variation up to a maximum density of 1.2 pers/m².

The rugby game is the event with the lowest density levels reached (up to 0.55pers/m²) and achieved flowrates (42.7 pers/m²min), while the concert with the female pop singer has the highest flow (57.7 pers/m²min) and the football event has the maximum density of 1.2 pers/m². These results may be expected given the relatively low maximum density produced – not enabling larger flowrates to be produced.

Summary flow and density outcomes for the free flow conditions during the four events are shown in Table 2. It is interesting that the ranking of density levels and flowrates are not aligned – somewhat supporting the discussion above that (a) the demographic and (b) the social interaction/grouping may be affecting the crowd movement and performance – rather than just the physical constraints imposed by the number and proximity of the crowd.

Fig. 5 shows the velocities generated across the four events for all the data collected (including data representing the impact of the Stop-Go procedure). Given the method used to derive these velocities (described above) and reduced sample sizes, the four Stop-Go phases have been combined (where present). It is apparent that at lower densities (below 0.5 pers/m²) the Rugby data-set typically produces lower velocities in comparison with the other events given the range of

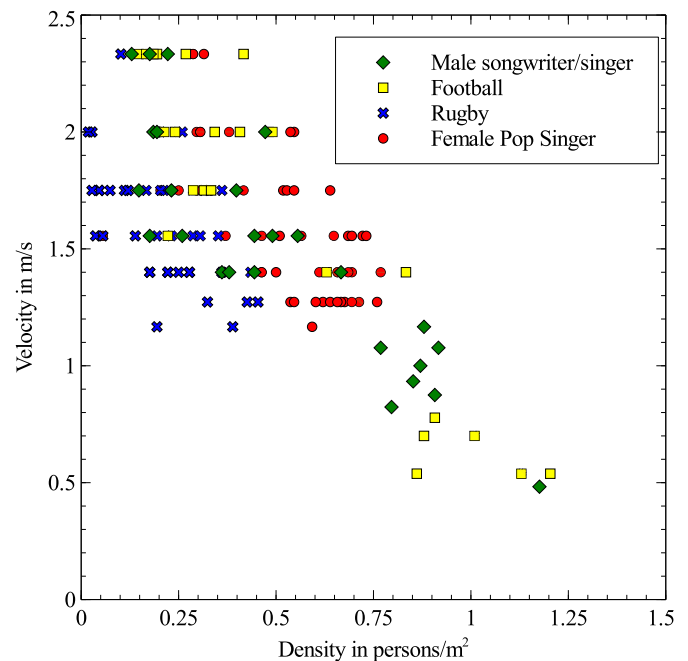


Fig. 6. Scatter plot of the relationship between the density and velocity for all four events in free flow conditions. Number of data points: Male songwriter/singer: 26, Football: 29, Rugby: 41, Female Pop Singer: 56.

conditions faced. The two events that generate the highest densities (football and male singer/songwriter) are also the two events where the Stop-and-Go system was used and where higher densities were expected. These spectators experienced the widest range of densities and produce a relationship where velocity is negatively affected by rising density across this range. During the rugby and female pop singer concert, the velocity never decreases below 1.2 m/s. This is given the narrower range of densities and the spectators not being constrained by the surrounding conditions. All four events have a maximum velocity of 2.3 m/s.

Fig. 6 shows the velocities generated across the four events for the free flow data collected (i.e. not affected by the Stop-Go procedure) – a sub-set of the data shown in Fig. 5. It is apparent that a narrower range of densities is produced with an overall maximum density of 1.2 pers/m² produced during the Football event. All four events again have a maximum velocity of 2.3 m/s as these were produced during free-flow conditions. The female pop singer concert data-set produced an equal or higher velocity ranges than the other events for comparable densities. This might be expected given the reduced footprint of teenage spectators and narrower velocity range. These factors are deemed to affect both the

Table 3
Descriptive summary of velocity data from the four events (free-flow conditions).

Velocity (m/s)	Football	Concert: Male singer/songwriter	Rugby	Concert: Female pop singer
Min	0.54	0.48	1.17	1.17
Max	2.33	2.33	2.33 ^a	2.33
Average	1.74	1.50	1.60	1.64
St. dev	0.63	0.48	0.26	0.32

Density (pers/m ²)	Football	Concert: Male singer/songwriter	Rugby	Concert: Female pop singer
Min	0.15	0.13	0.02	0.06
Max	1.20	1.18	0.45	0.77
Average	0.45	0.50	0.22	0.49
St. dev	0.32	0.30	0.12	0.18

^a Equivalent maximum speeds are generated given simplifying assumptions made regarding the path adopted by the pedestrian sample.

space expectations as well as minimize the impact of groups on travel velocity.

Summary velocity and density outcomes for the free flow conditions during the four events are shown in Table 3. Although this addresses the same events represented in the data shown in Table 2, the data extraction method employed is different; however, the density ranges and averages are comparable providing some confidence in the data presented below.

The highest densities and widest range of densities were achieved during the football event and the male songwriter/singer concert. The densities produced in the rugby game and female pop singer concert only reached 0.45 per/m and 0.77 pers/m² respectively. The velocities produced were quite similar across the four events (ranging from an average of 1.5 m/s (Male Concert) to 1.74 m/s (Football)).

5. Discussion and implications

A range of factors have been identified as influencing the results of the egress observations. The factors present include: the population density, the body footprints of the spectators, the innate velocities of the populations, the propensity to move with others forming groups, and the cohesion between the groups present. Given the range of factors present and that their interaction under different conditions, the average performance (be it flow or velocity), is unlikely to be as instructive as might normally be the case. Equal importance should be given to the underlying conditions – their constraint on the egress performance that might be achieved as opposed to their direct impact on spectator movement.

The female pop singer crowd included a large proportion of teenage girls which in most cases have a smaller body area (footprint) than an average adult male. This implies that they have more space per person that allows them to be less constrained by the population density (having comparatively more distance between them and the people around them) and then be more likely to achieve their chosen velocity. This implies that more people can fit in the same space whilst achieving comparable velocities (effectively experiencing the conditions of lower densities). The flowrate analysis suggested that egress during the female pop singer concert resulted in slightly higher average population densities, even though it is within a narrower overall range of densities. During this window, this population produced the highest average flowrate. Despite the female pop singer concert not producing the highest average velocity, it produced a narrower range of velocities (between 1.17 and 2.33 m/s) than the football game crowd (0.54–2.33 m/s), which had the highest average velocity. This may have been due to the groups of teenagers moving at the rate of their slowest member (narrowing the overall range of velocities).

Given the higher walking velocity and the low density, the flow including teenage girls might achieve higher levels than for the other events. This means that the flow/density relationship might shift along the density x-axis as the constraining impact of density is reduced. Similar findings can be found in the literature, where smaller populations (e.g. a Japanese population in this case [21]) corresponded to flows as high as 155.5 pers/m²min (2.59 pers/m²sec). However, the likelihood of increased flow is reduced through the constraining impact of group behaviour within this flow.

The football game took place during the winter; hence people were wearing bulkier winter clothes and taking up more space. The spectators at this event kept more distance to each other (given reduced grouping, allowing more individual movement) and in line with previous findings investigating people wearing winter jackets [9]. This is reflected in the wide range of velocities produced (0.54–2.33 m/s). This means that fewer people could pass the line out from the control volume at the same time which in turn resulted in a lower flowrate – exaggerating the impact of density on velocity. Although the average velocity is high (1.74 m/s) the achieved flowrate is relatively low (27.7 pers/m²min) in comparison with the case of the rugby game and the female pop singer concert.

The complete data-sets are instructive as to the conditions that might be present at such events – rather than providing insights into unaffected, free-flow crowd dynamics. The highest densities occurred when the Stop-and-Go system was used (football game and male singer/songwriter concert) – up to 1.85 pers/m². The maximum density observed for all events was at the concert with the male singer/songwriter, during a stop (see Fig. 3). The spectators at this event were mostly couples or smaller groups of friends who walked closely together – exacerbating the density present through clumpier flow generated through grouping. During a stop, attendees at the concert could more comfortably stand closer to each other. At the football game, where the crowd consisted mostly of men, the spectators seemed to want to keep more distance to each other.

The event with the lowest densities was the rugby game. This is likely linked to the population demographics (age range and the size of the people attending the rugby event) and the less cohesive grouping – fewer teenage groups and fewer couples. The number of people passing through the control volume were also lower than for the other three events. This event also had the lowest velocities despite the low density. A possible explanation as to why the walking velocity was low is that during this event there were the presence of more elderly people reducing the overall average velocity. The event also ended in the afternoon rather than in the evening (thus people not rushing to go home). Given the low density and time of the day, people seemed more relaxed and walked in larger groups while talking to each other. At this event, the flow of people was also not unidirectional, and this might have affected the velocities of the crowd leaving the stadium.

This study has several limitations. Firstly, the quality of the videos and the angle of the camera might have affected the counting of the people which affects the accuracy of the results. Due to these factors it is likely that some people have been missed out during the counting for the densities and flows. Uncertainties in the control volume counting are estimated to be maximum up to 5–10 people for higher densities and 1 person for the low densities, for a sample. Furthermore, the assumed distance covered when determining the velocity might have resulted in a systematic error in estimation. The maximum uncertainty here is estimated to be approximately 1 m. Secondly, the qualitative observations have been made without questioning the spectators – they have been inferred from visual evidence. Thirdly, it should be acknowledged that many factors might have influenced the behaviour of a crowd during these events that are not accounted for here. This may include factors such as motivation and alcohol consumption [22]. 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 game/event [23]. Those factors, along with several other potential influencing factors should be object of dedicated studies.

6. Conclusions

Crowd composition can play an important role in egress performance, thus should be taken into consideration in egress and evacuation planning. This has been demonstrated by collecting four egress movement data-sets at events in a stadium including different types of crowds.

The difference in performance is likely linked to the body area occupied by different crowds (e.g. young teenage girls attending a female pop concert versus adult males attending a football match) and the social interaction between members of the crowd (the number of groups and the extent of their cohesion). The observed flowrates were all below 60 people/m²min, which is significantly lower than the maximum value (82 people/m²min) recommended in the latest Guide to Safety at Sports Grounds (the sixth edition of the “Green Guide”). The observed behaviour and flowrates of different crowds during stadium egress suggest the need to carefully consider the impact of crowd composition when planning stadium egress including emergency evacuation.

This study demonstrates that lower flowrates might be considered in external areas of stadium egress (i.e. the primary routes of egress in

which large crowds from multiple stadium exits converge and move collectively towards transport hubs). The flowrates used for planning should consider crowd composition, as well as group behaviours as this may impact the clearance times in both egress and evacuation scenarios. This study adds to our understanding of realistic flowrates in external areas and provides new, lower benchmarking figures which may be considered when planning and simulating egress and emergency evacuation. However, further work is needed, to further understand the key differences between demographic composition and group behaviours, and their impact on egress and evacuation flows.

Declaration of competing interest

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

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