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Review article

A review of studies on understanding crowd dynamics in the context of crowd safety in mass religious gatherings

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ABSTRACT

Understanding the principles and applications of crowd dynamics in mass gatherings is very important, specifically with respect to crowd risk analysis and crowd safety. Historical trends from India and other countries suggest that the stampedes in mass gatherings, especially in religious events occur frequently highlighting the importance of studying the crowd behaviour more scientifically. This is required to support appropriate and timely crowd management principles, in the planning of crowd control measures and provision of early warning systems at mass gatherings. Common pedestrian behaviours in crowd like group formation, self-organization, leader follower effect, queue formation and bottleneck conditions have substantial influence on crowd dynamics. It is important not to let a single aspect go overlooked with respect to mass gatherings since it can lead to major stampedes. Kumbh Mela, one of the largest mass religious gatherings in the world, features these different crowd scenarios observed often in the same event area and thus provides a unique opportunity to study the crowd behaviour in a holistic way. Understanding these pedestrian behaviours and having a clear understanding of the normal behaviour may provide opportunities to change crowd dynamics and overcome the adverse effects resulting in safer mass religious gatherings in future. This paper provides an exhaustive review of the current understanding of crowd dynamics and explores the modelling techniques that are available to enhance crowd safety. The purpose of this literature review is to improve the understanding of crowd dynamics,and highlight the research gaps in the context of crowd safety in mass religious gatherings like Kumbh Mela.

1. Introduction

Pedestrians are an important element of transportation system since every person's trip begins and ends in walking. However in spite of its importance, pedestrian needs are often not considered effectively in the design and planning of transportation system particularly in developing economies like India. The term pedestrian and crowd complement each other. Pedestrian mob under the influence of psychological and other relevant factors starts behaving in unpredictable manner which becomes difficult to manage according to the norms of traffic engineering characteristics and is termed as pedestrian crowd [85]. Understanding and modelling how pedestrians behave individually and in groups in various situations, can help crowd events become safer.

However, pedestrian behaviours in public locations in a normal situation and in mass gatherings are considerably different. A mass gathering is when more than a specified number of persons at a specific location for a specific purpose gather for a defined period of time [21]. Mass gathering events have an enormous potential to place a severe disaster on the crowd. A mixture of high crowd density, restricted points of access, poor crowd control, and lack of complete information of the areas and activities can lead to situations of disaster [79]. Mass gatherings can be festivals, religious observances, sporting events, concerts and political rallies. Among these, mass religious gatherings are quite common and frequent in India and some other countries. Therefore it is important to understand the impact of crowd profile, tangible or intangible incident, psychological characteristics, weather conditions, and unfamiliar evacuation routes on crowd dynamics and crowd safety in mass religious gatherings. Also mass gatherings lead to increase in critical health risk when compared to other natural gatherings [81]. The health risks identified in one of the important mass religious gatherings in India, Sabarimala, includes outbreak of food and water-borne diseases, gastrointestinal illnesses, myocardial infarction (cardiac issues), outbreak of person-to-person diseases, allergic reactions, air-borne diseases, exacerbation of underlying medical conditions (asthma, BP, diabetes etc), animal and insect bites, human stampedes/ crowd disasters, structural collapse, and sun stroke out of which

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outbreak of person-to-person diseases and human stampedes/crowd disasters are picked out as the major health risks causing situations [45].

1.1. Background-mass religious gatherings

The Maha Kumbh Mela, the Hajj and the Shia procession to Karbala are some of the biggest mass gatherings of humanity. Kumbh Mela is touted as the largest religious gathering, and involves the pilgrimage of estimated 100 million Hindus to a sacred river in a span of one month. Many of the previous versions of this event have been marred by accidents and deaths. In 1954, the Allahabad Maha Kumbh took away the lives of more than 800 people due to the outpouring crowd that broke through the barriers splitting them from a procession of sadhus (holy men) from various akharas (camps of holy men) bringing out a severe stampede [4].

As reported in news articles from time to time, there have been many incidents that happened in Hajj in certain years that have caused loss of lives due to crowd movement. Almost half of these deaths occur at extremely high densities due to asphyxiation and half occur at comparatively low densities due to percussion on fallen pedestrians. The September 2015 stampede had taken 2236 lives due to progressive crowd collapse [1]. The stampede, which resulted due to overcapacity and formation of shockwaves, occurred at a place which was not previously identified as a serious bottleneck.

The stampede in Shia procession on August 31, 2005 took nearly 1000 lives on Al-Aaimmah Bridge, which crosses the Tigris River, in the Iraqi capital of Baghdad. This stampede occurred due to rumors of an imminent suicide bomb attack that panicked many pilgrims which led them to flock to the closed bridge. The pressure of the crowd caused the bridge's iron railings to give way, dropping hundreds of people 9 m (about 30 feet) into the Tigris River [3].

2. Kumbh Mela- India's largest mass religious gathering

India is a land of festivals due to its diverse religions and cultures [29]. The number of people participating in religious gatherings is always higher than those participating in entertainment and political occasions. There are recurring stampede incidents that occur at same venue which proves the fact that proper crowd risk management strategies should be brought out to prevent future stampedes. Almost 79% of stampedes in India occur in religious places [26]. Also, there have been a total of 3126 incidents of stampede in the country from 2001 to 2014, in which 2421 people have lost their lives [2]. Yet, the true picture and the scientific reason behind these remains a big question.

Kumbh Mela is the largest Hindu pilgrimage in which more than 100 million estimated people gather to worship God and take a holy bath in a sacred river with a belief that it cleanses their souls leading to salvation. Kumbh Mela is organized at four different places in India by rotation: Haridwar, Ujjain, Nasik and Allahabad and the holy bath is performed in the river Ganges, Shipra, Godavari, and confluence of Ganges, Yamuna and mythical Saraswati, respectively. Kumbh Mela at any given place typically happens once in 12 years i.e. at a difference of 3 years by rotation on an average.

2.1. Unique aspects of Kumbh Mela

Kumbh Mela welcomes people from various places within India and across the world. Large numbers of devotees from rural areas participate in PanchkroshiYatra (annual religious walkathon), where the devotees walk from their villages to the Ujjain city to take a circuitous route of 118 km around the city covering a large number of temples and a holy bath in the sacred river, in a limited span of five days. In the recently held Kumbh Mela (Simhasth-2016, Ujjain, India) around 0.6 million people participated in this yatra during hot summer time of May with temperatures above 40 °C. Fig. 1 depicts the crowd in PanchkroshiYatra held in recent Kumbh in Ujjain, India during 22nd April to 21st May 2016.

Fig. 1. Panchkroshi Yatra in recent Kumbh Mela held in Ujjain, India during 22nd April to 21st May 2016.

One of the unique aspects of this yatra is that most of the participating individuals come with a spiritual mindset and carry just a head load in terms of their luggage containing basic subsistence materials. Considering the time constraint, the movement of people is very fast even at high densities and they continuously walk with just intermittent stops (in farm fields) for couple of hours in a day for food, rest and relieving. Therefore, understanding crowd dynamics of such events can bring out unique aspects with respect to crowd risk.

Kumbh Mela is one mass religious event that gives opportunity to study all the typical situations of crowd dynamics observed in such events. The crowd control measures are not preplanned and so the scenario of crowd is different every day. Some days vehicular movements are restricted on main corridors and some days they are allowed. The barricades are changed dynamically based on the crowd densities. The routes to various activities are altered randomly without proper information or sign boards for the people. These may create chaos among the participants and could be a possible cause of stampede.

The levels of heterogeneity in terms of the mix of people (Sadhus, rural, urban and foreign people) is more in such mass religious gatherings in India. *Sadhus* are holy men who devoted their lives to God who have a mix of behavioural characteristics, with some of them being more assertive and aggressive in such mass religious gatherings with their behavioural and psychological characteristics. Rural people are those who come from villages/rural areas outside the city with spiritual mindset and who might be illiterate to read and understand signs and warnings. They will often follow the crowd blindly. They carry heavy loads which may affect their walking speeds. They always come in groups of varying size with a mix of men, women and children and may not have complete information of the areas, with many of them not carrying smart phones or even feature phones, reducing their access to information through digital means. As these groups move in the crowd, men will typically form the soft boundary (often holding hands) with their women and children in the middle, which makes the group act like an amoeba moving in a floating medium. Urban people are from cities generally having adequate information about the places. Many of the foreign participants are not spiritually inclined but mostly adventure-seeking. Accordingly, their behaviour will be different from the rest. Fig. 2 shows the heterogeneity among the people who visit Kumbh-sadhus, rural, urban and foreign population.

The pedestrians participating in such mass religious gatherings can be classified as follows:

- Goal directed- participants who are aware of the events and activities that take place in Kumbh and are clearly directed towards their goal while moving
- Goal seeking- participants who doesn't have complete information about the events and activities and are seeking information and clues to reach their goal

a. Sadhus (Holy men) b. Rural Population c. Urban and Foreign Population

Fig. 2. Heterogeneity among the people who visit Kumbh-sadhus, rural, urban and foreign population.

- Goal identifying- participants who are completely unaware of the events and activities or participants who are adventure seekers and who simply follow the crowd

There are different activities that are performed in Kumbh Mela which are typical in most of the bigger or smaller mass religious gatherings in India. They are visiting Akharas (camps) to worship gurus (spiritual leaders), participating in spiritual lectures, events at akharas, participating in processions/yatras, visiting temples and taking holy dip in sacred river. Further, the Kumbh Mela generally occurs in summer with high temperature in the places where it is held. The temperature varied from 39 to 48 degree Celsius in the recent Kumbh Mela that was held in Ujjain in 2016. Therefore, the levels of heterogeneity, the types of pedestrians participating, the different activities that they perform, the weather conditions, stochastic crowd control measures, improper planning etc. makes Kumbh Mela a typical crowd concentrated event to study the potentially critical dynamics of crowd. A more scientific data collection and analysis is required to understand why stampede occurs in such situations so that proper measures can be effectively taken to avoid such stampedes. Fig. 3 shows the massive crowd in recent Kumbh Mela held in Ujjain, India during 22nd April to 21st May 2016.

3. Studies on pedestrian characteristics

Pedestrian behaviour is an important aspect for planning and management of mass gatherings. The investigation of pedestrian behaviour is an ideal starting point for the development of general quantitative behavioural models. Trying to capture every element of pedestrian movement is a very complex task. However for an efficient behaviour model to predict the stampedes that are likely to occur and to provide an early warning system, it is essential to penetrate into pedestrian behaviour parameters as deep as possible.

The behaviour of Indians and that of others is very different in a crowd. A study conducted in 2009 tested the walking speeds of Germans and Indians. The results say that at low densities the speeds of each nationality are similar, but as the density increases, Indians walk faster than Germans. Also, the study says that Indians are not bothered about bumping into other people [17]. This study reveals some interesting behaviour of Indians in a crowd. The behaviour of Indians, particularly in mass religious gatherings, is aggressive even in high density conditions and they are least bothered about collision with other people leading to transfer of forces through body contacts, which can substantially raise the crowd safety risk. Therefore pedestrian behaviour in mass religious gatherings in India, like Kumbh Mela, need to be studied more scientifically in the context of crowd safety. Inferences from literatures on various characteristics of pedestrians and comments in the context of crowd safety in mass religious gatherings are summarized in Table 1

4. Analogous systems

Crowd and collective behaviour can be considered as synonyms. Experimental methods of investigation previously applied to the study of animal collective behaviour can be successfully transferred to the study of human interaction laws and to collective phenomena emerging from them [24,25,59], even though the behavioural and cognitive complexity of humans are greater. Also, fluid and granular flow theories have been applied to study pedestrian behavioural characteristics. The following table depicts the collection of literatures on analogous systems to pedestrian flow.

As it can be seen from Table 2, researchers have compared pedestrian flow with a variety of analogous systems existing in nature. Fluid flow analogy is the most widely used among them where the crowd is considered as a flowing continuum. Unlike a classical fluid, the crowd

Fig. 3. Massive crowd in recent Kumbh Mela held in Ujjain, India during 22nd April to 21st May 2016.

Table 1
Inferences from literatures on various characteristics of pedestrians and comments in the context of crowd safety in mass religious gatherings.

Sl. No	Pedestrian Characteristics	Author	Inference	Comments in the context of crowd safety perspective in mass religious gatherings
1	Dynamic group formation	[20]	One third of the population observed at 18 different locations are in groups of at least 2 members	In mass religious gatherings, people usually come in groups with a common objective. Therefore, inter group interaction as well as interaction with other non-group members will be more. People in group will be dynamic when an evacuation situation evolves. Therefore, it is very important to study group dynamics not only in normal but also in evacuation situations so as to ensure crowd safety.
		[18,12]	Three quarter of the crowd in a football event were in groups	
		[78]	Proportion of people being in groups is majorly influenced by the neighboring environment	
		[19]	Intergroup interactions are limited but two-thirds of Hajjis interact with people from other countries often	
		[61]	Frequency of people in groups will be higher in leisure areas	
2	Walking Speed	[38]	The desired speeds of pedestrians in crowd are Gaussian distributed with a mean of 1.34 m/s and standard deviation of 0.26 m/s	In mass religious gatherings, like Kumbh Mela, the walking speeds vary because of the heterogeneity of people and their aggressive levels, the group sizes and the nature and location of activities they participate. A previous study on Simhasth 1992 shows a speed range from 0.8 m/s to 1.5 m/s and the spread range of speed was more in the city than during normal days([85].
		[58]	Pedestrian walking speeds in groups in Western countries are greater than Asian countries	
		[88]	Pedestrians always prefer to walk with their comfortable walking speed though it will be different in different density setup	
		[68]	Passenger travelling in groups in airport have considerable waiting time at the security check process	
		[61,75]	Group speed reduces with increase in number of members in the group	
		[70]	Splitting of groups into sub-groups decreases the group size and increases the walking speed of the sub-group	
		[52]	Existence of co-passengers will increase the dwell time considerably	
		[14]	Speed-Flow-Density relationships are different in different studies as the data collection and representation are different in all cases. The results give a nonlinear relationship between speed and density for pedestrians in Indian conditions with different cultural setup when compared to other studies.	
3	Walking Direction	[64,88]	Studies have proven that pedestrians have a preferred side	The direction of walking depends on activities of pedestrian. In case of mass religious gatherings, the purpose of visit will be the same for all pedestrians. Therefore the direction of walking will be the same. But in the context of mass religious gatherings like Kumbh Mela, the directions can be different in spite of having the same purpose of visits because of the sequence of activities that people wish to perform. Some people might prefer to visit akharas after taking the holy bath and some might prefer to visit the temple after taking the holy bath. So there will be movement of people towards different destinations. This may cause hazard in terms of safety for the crowd.
		[27]	Pedestrians choose the fastest route to reach their destination	
		[37]	Pedestrian show an aversion to move in opposite direction against the crowd to take an alternative route even if the direct route is crowded and moving at a slower pace. Also, pedestrians always prefer to move in straight direction even though the alternative route is of same length	
		[44]	The average walking speed will not go to zero even at local densities of 10 persons per meter square	
		[61]	In case of head on encounters pedestrians have to choose whether to evade the opposite passenger in right or left side which reduces the walking speed significantly	
4	Emergency Norms and Situations	[47]	Alternative exits are not used more efficiently during escape situations	Understanding the situation of emergency and panic is very important in mass religious gatherings as the conditions are dynamic. An Early Warning System is very much necessary to predict the kind of panic situation well ahead, so as to avoid stampedes and accidents that are likely to occur and to provide alternatives based on the circumstances.
		[5]	Emergency norm theory was developed by considering evacuation time and group size and social interactions were taken as the important factors for time of response and evacuation	
		[37]	Conventional methods of handling emergency situations does not always guarantee the avoidance of big jams, serious obstructions, and catastrophic blockages	
		[89]	Directional sounds for the exits could considerably reduce the unnecessary jamming and escape time during evacuation situations	
		[42]	Due to inadequate knowledge of available exits, people try to exit through first identified exit leading to unnecessary jamming	
		[56]	Emergency Pedestrian Modelling System is developed to evacuate a particular location rather than reaching the destination considering the evacuation time along with the personal characteristics of pedestrians, number of people in the scenario, obstacles in the environment	
5	Bottleneck condition	[62]; [72]	Wider width in the downstream of the bottleneck will lead to higher flow	In mass religious gatherings, like Kumbh Mela, millions of people participate in yatras/processions where they have to walk along the rural roads and uneven and narrow streets in the city center. Such roads and streets have irregular geometric conditions and the section becomes narrow from wide or vice versa which causes bottleneck effect leading to propagation of shockwaves. This can cause serious hazard in terms of safety for the crowd and has to be studied with greater importance in order to avoid stampedes.
		[37]	The flow at bottleneck can be improved significantly by providing a funnel-shaped section	
		[40]	The flow increases in step wise manner along with the lane formation but not a linear function of bottleneck width especially for unidirectional flows. Effective width of the bottleneck and the number of layers that can be formed in the available width are required to calculate the capacity of the bottleneck	
		[76,72,51]	Linear relation is observed between pedestrian flow and bottleneck with a slope of 1.9 m/s with bottleneck width ranging between 0.7 m to 5 m	
6	Leader follower effect	[15]	The presence of a leader increases the probability of imitation	Leadership is expected to result in an increase in behaviour clustering. Leader follower

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Table 1 *(continued)*

Sl. No	Pedestrian Characteristics	Author	Inference	Comments in the context of crowd safety perspective in mass religious gatherings
		[50]	The followers will control their walking speed so as to walk behind their leader	effect will be different during normal and evacuation situations. During KumbhMela, the leader-follower effect is prominent as a lot of spiritual gurus at various levels of hierarchy move with their follower in the mixed crowd. Therefore it is essential to study the behaviour of leader-follower during both the situations so that the safety of crowd is ensured.
		[69]	More number of leaders will lead to increased evacuation time; reason behind is that the followers get indecisive of what leader to follow. In evacuation situations the group members will be dynamic.	
		[61]	At low densities, group members walk in horizontal formation. At high densities middle pedestrian tends to stand back generating a 'V'-like formation	
7	Self-organization phenomena	[31]	The number of forming lanes is in dependence of the width of the walkway	It is inferred that self-organization phenomena arises due to the repulsive interaction between the pedestrians in opposite direction. These interactions at extreme densities and the resulting crowd dynamics are also responsible for stampedes which endanger the safety of the crowd and so it is very important to study this behaviour of pedestrians. During events like KumbhMela, the self-organizing behaviour is commonly observed due to weak boundary conditions, random changes in crowd movement regulation etc., often leading to situation of crowd risk.
		[37]	Self-organization means that these patterns are not externally planned, prescribed, or organized, for example, by traffic signs, laws, or behavioural conventions. Instead the spatiotemporal patterns emerge through the nonlinear interactions of pedestrians	
		[35]	At extreme density conditions lanes are destroyed by increasing the fluctuation strength which leads to the transition of a moving crowd to "freezing by heating"	
		[34]	In order to avoid collision with the opposite flow, pedestrians tends to move sidewards forming lanes. The number of lanes formed depends on the width of the street and pedestrian density. Lane formation can increase the capacity of the facility	
		[40]	Under saturated conditions, dynamic layers are formed with lateral distances less than the average shoulder width of the pedestrians, denoting that the layers get merged and move with same speed	
		[60]	The effect of one person trying to walk faster than the people around him in a dense crowd is to force an opposing lane of pedestrians to split in two, which has the effect of breaking up the lane next door, and so on. Everyone moves slower as a result	
		[61]	Lane formation leads to a more effective pedestrian flow, since time consuming avoidance maneuvers occur less frequently	
8	Queue formation	[20]	Queue formation exhibits joining and leaving behaviour which results in a truncated Poisson distribution for the group size	Situations in mass religious gatherings like Kumbh Mela, are very dynamic and so the reasons for queuing may be different in different scenarios. Queuing may be due to extreme density crowd which is the most common situation, Cul-de-sac effect at the banks of river where people have to wait for taking holy dip, processions, queuing inside the temple etc. All these circumstances have to be considered when crowd safety is in focus particularly when everyone is goal directed and is moving with the same goal in the situation of uncertain waiting time, the destination being not visible etc.
		[32]	Queue propagates in wave-like manner to the end of the queue and the distance to move forward increases	
9	Extreme density crowd	[77]	At high densities and low velocities, the utilization of space is optimized and it was observed that the participants set their feet far right and left from the line of movement in a single file controlled experiment overlapping the space of the participants in the front.	The maximum density in Kumbh Mela is observed by authors to be 7 persons per meter square (from the studies conducted by the authors) which is similar to the conditions in Hajj which was considered as extreme density crowd. Therefore understanding crowd behaviour and crowd risk situation under extreme densities is important to develop an effective prediction system.
		[36]	Previous uncontrolled experiments under critically high density crowds is the one conducted at Hajj. Stop and go waves are observed when the maximum density reaches about 7 personsper meter square.	
		[44]	Safety in a mass crowd is determined by maximum occurring density but not by average density	
		[63]	In large crowd, people moving in particular direction will cause pressure. The critical boundary begins at a crowd density of 6 personper meter square	
		[55]	The greater the number of people in whom the same emotions can be simultaneously observed, the greater the spread. The individual under the influence of emotion losses the power of criticism and slips into the same emotion	
		[7]	A common stimulus prepares two individuals for the same response and when they are so prepared, the sight of one making that response releases and heightens that response in the other	
10	Psychology of crowd	[83]	An emergent norm perspective was developed with an idea that even in the most violent and dangerous crowds, there is also social interaction, in which a situation is defined, norms for sanctioning behaviour emerge, and lines of action are justified and agreed upon	The behaviour of crowd is always emotionally determined. Fear, anger and rage are the fundamental emotions of people in crowd which gets aggravated because of the circumstances. Studies reveal that emotions are influential and contagion. In mass religious gatherings like Kumbh Mela, Hajj etc., aggressiveness of people should be the most important aspects of psychological characteristics. The psychological levels of people have a great influence on crowd safety and hence it is very essential to consider these characteristics as one of the pedestrian behaviours so as to ensure safety of the crowd.
		[15]	The organization of minds of people varies according to the exciting or the panicking causes that the people are facing apart from their race and composition. In heterogeneous crowds, crowd will act more ferocious. Group mind makes people feel, think and act in a manner quite different from that in which each individual.	
		[91]	Directionally going with the crowd during evacuation reduces the time of looking for routes and exits whereas spatially going with the crowd causes an adverse effect	

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Table 1 (continued)

Sl. No	Pedestrian Characteristics	Author	Inference	Comments in the context of crowd safety perspective in mass religious gatherings
		[13]	Pedestrians in panicking situations choose to move to high density location rather than moving towards their destination	
		[53]	Social influence plays a vital role in deciding an individual's action	
		[22]	Psychological component of a crowd with three basic components- personality, emotion, mood, was incorporated into the virtual agents to simulate the emotional nature of mobs	
		[84]	Psychological Rating Index (PRI) can be used as an evaluating factor giving the potential risk level for the crowding behaviour at any instant of time and this PRI value can be used as a logical guide for safe pedestrian management system.	

has the ability to think. Since the crowds are rational and can therefore be expected to abide by scientific rules of behaviour [57], it will be more realistic if the pedestrian flow could be compared with similar systems. Sometimes crowd is compared with swarm behaviour. From a more abstract point of view, swarm behaviour is the collective motion of a large number of self-propelled entities, which is similar to movement of individuals in a crowd. From the perspective of mathematical modelling, it is an emergent behaviour arising from simple rules that are followed by individuals and does not involve any central coordination. In order to have a deeper understanding about the crowd behaviour in panic situations, experiments on mice escaping out of water has been conducted. The self-organization in crowd which produces complex and seemingly intelligent activities without any planning often resembles 'stigmergy' in animals. The insights developed from these analogous systems can be applied in a scientific stream in order to solve the complexities in crowd behaviour and improve crowd safety in mass gatherings.

5. Modelling and simulation

One of the most relevant and at the same time most challenging problem is panic stampedes, which is a serious concern during mass events. Despite huge numbers of security forces and crowd control measures, hundreds of lives are lost in crowd disasters every year. A high-performance video analysis of unique recordings of the Muslim pilgrimage in Mina/Makkah, Saudi Arabia suggests that high density flows can turn "turbulent" and cause people to fall [6,82].

There are different modelling approaches that are adopted while modelling the pedestrian flow. These models can be broadly classified as empirical models, analogy models, and simulation models. In each area, large numbers of such models have been developed by the various researchers.

5.1. Empirical models

Empirical models are deterministic in nature. If sufficient amount of suitable data is available these approaches can be used without much difficulty. These models can be applied in finding the aggregate behaviour of the pedestrians. As flow conditions are different at various locations and at various point of time, the pedestrian modelling by this approach requires huge amount of data for developing a realistic model. Collection of this large amount of data is uneconomical. Moreover it may not be possible to observe data for all ranges of flow conditions. Also the availability of long uniform sections having the minimum adjacent section influence is a problem in data collection. As these models are aggregate in nature they have limited use in development of standards.

5.2. Analogy models

Analogy models also come under deterministic models. For developing these models it is assumed that the pedestrian flow is analogous to fluid flow or hydrodynamic flow. The speed – density relationship is developed based on the continuity equation, which is an expression of conservation of mass.

Among the advantages, this approach provides valuable insight to various aspects of pedestrian behaviour and modelling and it can be used as a base model to derive macroscopic flow models. The complexity of formulation, dissimilarities between the pedestrian flow and the fluid flow, too many parameters in the model etc. are some of the limitations of analogy approach.

5.3. Simulation approach

Pedestrian behaviour on road ways can be improved by field research and field experiments of real-life pedestrian flow. However,

Table 2
Analogous Systems to Pedestrian Flow.

Author	Pedestrian behaviour/characteristics	Analogous system
[11]	Motion of pedestrian crowd	Motion of gases and fluids
[11]	Crossing behaviour of stationary pedestrian crowds	Moving pedestrians form river-like streams
[11]	Footsteps of pedestrians	Streamlines of fluids
[46]	Pedestrians walking in opposite directions	Viscous fingering
[87]	Dense pedestrian crowds which push forward	Propagation of shock waves
[37]	Pedestrian reaction to obstacles/ other pedestrians	Behaviour of an experienced driver
[33]	Pedestrian flow	Granular flows
[54,74]	Lane formation of uniform walking direction	Segregation or stratification phenomena in granular media
[67,90]	Bottlenecks- the passing direction of pedestrians oscillates with a frequency	Ticking hour glass
[71,86]	Self-organization of collective behavioural patterns	Bird swarms
[59,9,16,43]	Amplification phenomena-individual's preference is amplified by many other individuals	Group-living organisms
[92]	Pedestrian clog in narrow passages	Sheep herds, grain assemblies, colloids
[73]	Pedestrian under panic situations	Mice escaping out of a water pool
[8,23]	Pedestrian under panic situations	Ants dispersion
[69]	Following the leader	Cowboy followed by cattle

apart from the scientific problem of reproducing such experiments, costs and safety play a role of dominant importance as well. Due to the complexity of the pedestrian flow system, especially at critically high densities, analytical approaches may not provide the desired results. Therefore, pedestrian flow simulation models designed to characterize the behaviour of the complex flow system have become an essential tool in pedestrian analysis and experimentation.

Human behaviour is based on individual decisions. In building a mathematical model for the movement of pedestrians, one has to assume that these decisions show certain regularities (e.g. follow stochastic laws) [32]. This assumption is justified, because decisions and the behaviour of pedestrians are usually determined by utility maximization.

5.4. An overview of models for simulation of crowd dynamics

Over the decades, the simulation of pedestrian movement has been explored in a variety of ways. Many of the models are initially based on vehicle traffic systems, which are one dimensional. This is significantly different from pedestrian traffic, where it is not restricted to a single dimension. Many models of pedestrian behaviour have been proposed to uncover laws underlying crowd dynamics [10,80,41]. Among these, physics-based approaches are currently very common. Well-known examples are fluid-dynamic [30] and social force models [61,66,32], which are inspired by Newtonian mechanics. However it is difficult to capture the complete range of crowd behaviours in one single model.

5.4.1. Fluid flow model

The observations of pedestrian movements have shown that the pedestrian footprints in snow or quick motion pictures are similar to streamlines of fluids. Henderson [39] was the first to compare gas kinetic and fluid dynamic models to empirical data of pedestrian crowds and he assumed that there is conservation of momentum or energy. Helbing [32] developed a fluid dynamic model, in contrast to Henderson's approach, without using unrealistic conservation assumptions.

The similarity of the motion of pedestrian crowds with the motion of ordinary fluids can be best seen by comparison of quick-motion pictures of pedestrians with streamlines of fluids. Nevertheless, the fluid dynamic equations for pedestrians contain some additional terms, which take into account the intentions and interactions of pedestrians. Fluid dynamic equations are derived for the movement of pedestrians assuming that they are anisotropic [32].

5.4.2. Gas kinetic model

Gas kinetic equations are applied when pedestrians are distinguished into different types of motion [32]. Here quantities like “temperature” and “pressure” play another role as in ordinary fluids. It can be shown, that the “temperature” (that means the velocity variance) θ is produced by the variance of the intended velocities, the individuals want to move with. As a consequence, two contacting groups of individuals belonging to different types of motion can show different “temperatures”. This is the case, for example, on a dance floor. On the other hand, whereas a pressure gradient is compensating the effect of internal friction in ordinary fluids, for pedestrian crowds this role is played by the accelerating effect of the intended velocity. Therefore a hyperbolic stationary velocity profile is found instead of a parabolic one.

5.4.3. Social force model

The social force model simulates the microscopic movements of pedestrians. The motion of these pedestrians are described by subjecting them to 'social forces'. These forces are exerted by the pedestrians’ personal environment, as well as the interactions with other pedestrians in this context. This approach for modelling behavioural changes is guided by so-called social fields or social forces [49].

In 1995,Helbing and Molnar came up with a “social force” computer model that used insights from the way the particles in fluids and gases behave to describe pedestrian movement. The model assumed that people are attracted by some things, such as the destination they are heading for, and repelled by others, such as another pedestrian in their path. It proved its worth by predicting several self-organizing effects among crowds that are visible in real life.

Social force model is a multi-particle self-driven model introduced by Helbing et al. [35], analyzed by Parisi and Dorso [65] and then improved by Lakoba et al. [48]. Pedestrians are treated as particles subject to long-ranged forces induced by the social behaviour of individuals. The movement of pedestrians can be described with a main function, which determines the physical and social forces, and the induced velocity changes. Typical phenomena observed in actual evacuation, e.g. arching, clogging, faster is slower, are reproduced through the model.

5.4.4. Cellular Automata

Cellular Automata has been considered to be one strong tool in modelling various kinds of phenomena such as pattern formation of natural system, fluid flow, traffic flow, city logistic or economical activities. Cellular automata are suitable in the simulation of complex systems. Pedestrian flow may be observed as assembling of movement of each person. In the modelling by cellular automata, local neighbor rules and transition rules should be implemented to simulate time evolution of the phenomena to be considered, but these rules have large effect on the simulation result, and careful consideration is required in identifying these rules in such cases as pedestrian flow, no standard rules are available to describe the movement of each person in the

crowd.

5.4.5. Cognitive science approach

A cognitive science approach was proposed based on behavioural heuristics, which could capture the characteristics which other approaches failed to [61]. Heuristics are fast and simple cognitive procedures that are often used when decisions have to be made under time pressure or overwhelming information [28]. This is illustrated by the example of a player trying to catch a ball, which may be modeled in at least two ways: either an attraction force can be used to describe the player's motion toward the estimated landing point of the ball or the process can be described by a so-called “gaze heuristic.” This heuristic consists of visually fixating on the ball and adjusting the position such that the gazing angle remains constant.

6. Limitations and research gap

The following is the summary of limitations and research gaps from the literature review with respect to understanding crowd dynamics in mass religious gatherings.

1. A typical study on mass religious gatherings with heterogeneous mix of people, levels of participants, different activities that they perform, extreme weather conditions, and stochastic crowd control measures is still lacking in the current literature which have to be focused in order to study the crowd dynamics more realistically.
2. Fundamental speed-flow-density relationships and their shapes varies in different experimental conditions and cultural backgrounds. In some literature, data obey the basic linear relationship between speed and density but in some literature it takes a non-linear relationship. So there is a research gap in understanding these fundamental relationships between speed, flow and density in mass religious gatherings like Kumbh Mela.
3. In mass religious gatherings, people come in groups with common objectives. In some events like yatras, their walking speeds are higher as the flow is unidirectional and people are goal-oriented. But in the city center where Kumbh Mela happens, people walk in different directions at different speeds in spite of having common purpose of visits as the sequence of activities that they wish to perform differs. So there will be movement of people towards different destinations. Therefore, this stochastic behaviour has to be focused when group behaviour is studied.
4. In mass religious gatherings, like Kumbh Mela, millions of people participate in yatras and processions where they have to walk along the rural roads and uneven and narrow streets in the city center unlike other controlled setups. Shockwaves generated in such roads and streets having irregular geometric conditions and where the section becomes narrow from wide or vice versa has to be studied as this can cause serious hazard in terms of safety for the crowd.
5. The concept of dependency between the capacity of bottleneck and the width of the section is still not discussed clearly in an uncontrolled experimental setup.
6. In mass religious gatherings like Kumbh Mela, where the setup is completely stochastic due to weak boundary conditions, random changes in crowd movement regulation etc., situations of crowd risk is more. Also, the self-organizing behaviour can be different from the experiments conducted in a controlled setup.
7. For the safety of pilgrims in mass religious gatherings and to ensure an early response to any emergency situation/problem, a sophisticated and continuous monitoring system like an early warning system is very much required. The current state of the system captured and estimated through various sensors on sample basis coupled with crowd simulations and a crowd risk assessment model can possibly lead to development of an early warning system that can help predict situations of crowd risk in advance which can possibly be used by event managers to evaluate and deploy quick measures to diffuse the predicted situation of crowd risk.
8. A more realistic simulation tool is required to address the observed pedestrian characteristics, their collective behaviour in emergency situations, the dynamics of crowd, the psychological aspects of crowd etc., to produce results that compare the real data more favorably.

7. Summary and conclusion

This paper summarizes the various studies that have been done on crowd dynamics emphasizing on mass gatherings. It is seen that not much studies have been done in mass gatherings in uncontrolled setup except few like Hajj. Many studies are done in a controlled setup. In mass gatherings, crowd safety is the most important aspect that has to be considered as the circumstances in such uncontrolled setups are very dynamic. Therefore the objectives of this paper are (a) to provide a comprehensive review of the studies on crowd dynamics (b) to identify the limitations and gap in the current literatures (c) to provide a base or a guideline for future studies.

In this paper, the uniqueness of Kumbh Mela from other experimental setups for crowd dynamics is discussed. The important pedestrian characteristics that have great influence on their behaviour are studied and how they differ in the context of crowd safety in mass religious gatherings are dealt in more detail. Also, various traditional pedestrian modelling approaches are discussed. Large scale human activities have become more frequent especially massive entertainment events, religious gatherings, sports events etc. Crowd safety has become a critical issue causing the attention of security sector. This makes it meaningful to analyze the crowd dynamics and associated characteristics. This paper presents a comprehensive literature review of crowd dynamics in various scenarios-from controlled experiments which have comparatively lesser crowd density to uncontrolled experiments with critically high density like Hajj. Situations considered in most of the literature are rather simple except for the experiments conducted at Hajj.

Modelling and simulating the motion of realistic large dense crowds is a challenge. None of the current models can realistically model high-density crowds, under dynamically changing environments. Models for normal conditions does not suit for emergency situations on real ground. Emergency situation parameters should include the psychological factors to a greater extent as the behaviour of each pedestrian will be different in panic case. Therefore, for the safety of pilgrims in mass religious gatherings and to ensure an early response to any emergency situation/problem or to predict an emergency situation/problem, a sophisticated and continuous monitoring system like an early warning system is very much essential.

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