A roadmap for the future of crowd safety research and practice: Introducing the Swiss Cheese Model of Crowd Safety and the imperative of a Vision Zero target

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ABSTRACT

Crowds can be subject to intrinsic and extrinsic sources of risk, and previous records have shown that, in the absence of adequate safety measures, these sources of risk can jeopardise human lives. To mitigate these risks, we propose that implementation of multiple layers of safety measures for crowds—what we label *The Swiss Cheese Model of Crowd Safety*—should become the norm for crowd safety practice. Such system incorporates a multitude of safety protection layers including regulations and policymaking, planning and risk assessment, operational control, community preparedness, and incident response. The underlying premise of such model is that when one (or multiple) layer(s) of safety protection fail(s), the other layer(s) can still prevent an accident. In practice, such model requires a more effective implementation of technology, which can enable provision of real-time data, improved communication and coordination, and efficient incident response. Moreover, implementation of this model necessitates more attention to the overlooked role of public education, awareness raising, and promoting crowd safety culture at broad community levels, as one of last lines of defence against catastrophic outcomes for crowds. Widespread safety culture and awareness has the potential to empower individuals with the knowledge and skills that can prevent such outcomes or mitigate their impacts, when all other (exogenous) layers of protection (such as planning and operational control) fail. This requires safety campaigns and development of widespread educational programs. We conclude that, there is no panacea solution to the crowd safety problem, but a holistic multi-layered safety system that utilises active participation of all potential stakeholders can

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significantly reduce the likelihood of disastrous accidents. At a global level, we need to target a *Vision Zero of Crowd Safety*, i.e., set a global initiative of bringing deaths and severe injuries in crowded spaces to zero by a set year.

1. Introduction

Crowd safety has become an increasingly important concern in recent years due to a rise in mass gatherings and events worldwide. Ensuring the safety of large crowds has become a complex and multi-faceted challenge. Crowd Safety is mostly about prevention. Yet, there is little common knowledge about how to prevent accidents from happening. This means many practitioners mainly learn by practice. That way of learning could well be very dangerous given that human lives are at stake. This is why the management of crowds requires a coordinated effort between academics and practitioners to develop methodical and effective strategies and approaches. However, there remain many contemporary challenges facing crowd safety research and practice that need to be addressed to enhance our understanding of how to effectively ensure the safety of crowds and crowded places.

This paper aims to explore these challenges and provide a roadmap for the future of crowd safety research and practice from a joint academic and practitioner perspective. By examining the latest research, best practices, and case studies, we will highlight the key issues that need to be addressed in order to improve crowd safety. We will also examine the role of technology and emerging trends in crowd management and explore how these can be leveraged to enhance safety and security. Ultimately, this paper seeks to provide a comprehensive overview of the current state of crowd safety research and practice, identify key challenges and opportunities, and propose a roadmap for future research and practice, along with practical recommendations.

The content capitalises on an international initiative in this space, the *Crowd Safety Summit Australia*,[1] which brought together academics, practitioners, and industry leaders as well as national and international stakeholders to discuss the latest developments in crowd safety research and practice as well as the existing challenges. Drawing upon the expertise and experiences of the participants at the Crowd Safety Summit Australia, this paper will examine the latest research, case studies, and best practices in crowd safety management as well as the existing and potential technological developments. We will highlight the key challenges facing crowd safety research and practice, such as the need to balance safety and security with crowd experience, the importance of effective communication strategies, and the use of emerging technologies to enhance crowd safety.

The content begins by laying out existing challenges and underexplored opportunities in crowd safety practice while expanding on a range of key notions. This embodies a classification of broad types of risks to crowd safety as well as the general barriers that one can envision (and also exist in practice to varying degrees) to protect crowds from these sources of risk. This includes aspects related to (i) policy and legislation, (ii) planning, (iii) operational control, (iv) community preparedness and (v) incident response & impact mitigation. These notions are subsequently integrated with one another under the umbrella of what we refer to here as *The Swiss Cheese Model of Crowd Safety*. In doing so, we explain how a multi-layer system of safety protection for crowds can significantly mitigate the likelihood (and/or impact) of disasters. The model is based on the premise that every single layer of safety protection can be imperfect and subject to flaws, but a system with multiple layers of safety protection will not fail unless vulnerabilities at all individual safety layers align concurrently. We discuss what this model entails and what its layers are along with the potential benefits and barries of its implementation as well as a particular layer that is largely overlooked in current practice (i.e., the community preparedness layer). Finally, we conclude how translation of this model to standard practice requires effective communication and collaboration between various stakeholders of crowd safety. It is hoped that this paper will contribute to a greater understanding of crowd safety and inspire new approaches to the management of large-scale events and public spaces.

2. Definition of crowd science

Crowd science is a multidisciplinary field of study that focuses on understanding the behaviour of crowds and developing strategies to ensure their safety in various settings (O'Toole et al., 2019a; Still et al., 2020; Tatrai, 2021). The field draws on insights and techniques from a range of disciplines, including engineering, psychology, sociology, applied physics, applied mathematics, computer science and management (Haghani, 2021). The main aim of crowd science is to find explanations for crowd behaviour, identify the factors that influence crowd behaviour and the potential risks associated with gatherings of people. This includes identifying potential hazards, evaluating the likelihood and severity of harm, and developing strategies to mitigate or control the risks (Still, 2014). Crowd science also seeks to develop and improve the tools and techniques used in crowd management and emergency response. This includes developing models and simulations to predict crowd dynamics (Gwynne et al., 2015; Haghani and Sarvi, 2019f, 2023; Haghani et al., 2018), as well as developing protocols and training programs for emergency responders (Masterson, 2012).

The importance of crowd safety lies in its ability to prevent and mitigate the risks associated with large gatherings of people, such as stampedes,[2] overcrowding, and security threats (Au, 2001; Johansson et al., 2008; Raineri, 2016). Overall, the goal of applying the principles of crowd science is to promote safe and successful events and gatherings, while minimising the risks to participants and the public (Alkhadim et al., 2018; Raineri, 2013). As such, it is an essential field of study for anyone involved in event planning, emergency management, or public safety, and plays a critical role in ensuring the well-being of individuals and communities in various settings from sporting events and concerts to political rallies and religious gatherings (Feliciani et al., 2022c; Gayathri et al., 2017; Karthika et al., 2022; Koski et al., 2021; Subramanian and Verma, 2022). By implementing effective crowd safety strategies, anyone involved in ensuring the safety of crowds (e.g., event organisers and, venue operators, security firms, police, emergency services and local authorities) can minimise the risks associated with large gatherings and ensure the safety of participants and the public. Moreover, crowd safety is strongly connected to the prevention and mitigation of security threats. Large gatherings can be attractive targets for terrorist attacks, and the potential for criminal activity increases in crowded environments. Crowd safety strategies need to be assessed in relation to the deterrence and mitigation of security threats. This can include measures such as planning queue lines, detecting suspicious behaviour, avoiding high densities in crowds, searching or screening participants, increasing the deployment of security personnel, and implementing emergency response procedures.

[1] The event took place on May 22 & 23, 2023 at the University of New South Wales in Sydney, Australia.

[2] Although the term "stampede" is often misused (used inaccurately) in both scientific literature and media, there are occasions where this kind of accident does occur. The term is used here to refer to those events and not to events that may have been mislabelled as such.

3. Complexities in crowd behaviour

To be able to ensure the safety of a crowd, we first need to understand crowd behaviour. The study of crowd behaviour is complex due to a wide range of factors that influence how individuals behave in groups. Some of the key factors that make the study of crowds complicated include:

- *Heterogeneity in crowd compositions*: Crowds can be highly diverse, including individuals with different backgrounds, cultures, ages, and motivations. This diversity can make it challenging to understand and predict crowd behaviour (Gayathri et al., 2017; Kingshott, 2014; Larsson et al., 2021). Even within one event, crowd profiles can differ from stage to stage, or over time, and a crowd composition can well contain very different groups with different behavioural traits.
- *Dynamic nature of crowds*: Crowds are dynamic and constantly changing, which can make it difficult to predict and manage crowd behaviour. Factors such as the size and density of the crowd, changes in activities offered on location, as well as changes in the environment or context, can influence how individuals behave (Bosina and Weidmann, 2017; Haghani and Sarvi, 2017a, 2019b; Haghani et al., 2019c).
- *Multidimensionality of movement space*: Unlike vehicular traffic which is confined to a specified road segment with fewer degrees of freedom, the space of movement for crowds and pedestrians is less regulated and offers more degrees of freedom, making pedestrian traffic a more complex phenomenon to model. Also, compared to the little variations that exist in vehicular networks, pedestrian traffic takes place in a large variety of spaces (e.g., open spaces, built environments, different terrains etc.) adding further layers of complexity from a modelling point of view (Haghani and Sarvi, 2017a, 2018). The attributes of space itself can have big impact on crowd behaviour. Especially at events, where there could be a partially soft substrate, narrow passages, presence of queues and height differences.
- *The role of emotions*: Emotions can play a significant role in crowd behaviour (Bellomo et al., 2023; Laws, 2016; Singh et al., 2019), and can be highly contagious (Fu et al., 2014; Mao et al., 2020; Nicolas et al., 2016; Tsai et al., 2013; Wang et al., 2017). Emotions such as fear, anxiety, excitement, and anger can spread quickly in crowds, leading to changes in behaviour and potential risks (Aylaj et al., 2020; Templeton et al., 2015; Xu et al., 2019).
- *Communication*: Communication like signs, social media messaging, loudhailer messaging, and spoken words, have an important influence on crowd behaviour. In particular, when crowds need information to make the right decisions, communication is essential and needs to work effectively. Communication breakdowns can occur in crowds, particularly in high-pressure situations. This can make it difficult to provide information and guidance to attendees, leading to confusion, undesirable crowd behaviour and potential risks.
- *Group dynamics*: Group dynamics can also influence how individuals behave in crowds. Factors such as social identity (Drury et al., 2009a), conformity, and leadership can all influence behaviour, and can be very critical, but at the same time, difficult to predict or exogenously influence (Drury and Reicher, 1999).
- *Contextual factors*: The context in which crowds occur can also influence behaviour. Factors such as the purpose of the event, the location, and the time of day can all influence behaviour and risk (Haghani and Sarvi, 2016a, 2017a). Also, societal developments and events that happen elsewhere can have an effect on crowd behaviour at an event or crowded place. This was the case in recent years when terrorist attacks were taking place and crowd sometimes overreacted to a sudden sound or movement.

These specific characteristics have made the transferability of vehicular traffic flow models and theories to crowds questionable. Custom models have been developed to replicate the motion of crowds, ranging from fluid-type models (describing crowds as a continuous body) to individual-based models, as well as the hybrid between the two. Similarly, general theories of group behaviour in psychology have proven inadequate for describing crowd behaviour, and as a result, specific psychological theories have been proposed to explain various crowd phenomena (Drury, 2020; Laws, 2016; Sime, 1995; Templeton et al., 2015). One of the most frequently cited theories in crowd psychology is *Social Identity Theory* (Drury, 2018). Crowds can be seen as a social group, and social identity theory suggests that people identify with groups to increase their self-esteem and sense of belonging (Alnabulsi and Drury, 2014; Alnabulsi et al., 2018; Alnabulsi et al., 2020; Drury et al., 2019).[3] Sport fans may, for example, adopt the identity of their favourite team as part of their own self-concept. When fans feel a strong sense of social identity with their team, they are more likely to experience group cohesion. This means they feel a sense of togetherness and solidarity with other fans. In the context of religious crowds, this theory suggests that individuals may feel a strong sense of belonging and identity with the group.

Crowd sociology has, for example, shown that "fan violence arises from the dynamic interplay between individual, interpersonal, situational, social environmental, and social structural factors" (Spaaij, 2014). Research suggests that factors like anonymity, group size, and alcohol consumption scan increase the likelihood of aggressive behaviour. However, other studies have shown that fans can also use the collective experience of the crowd to regulate their own aggressive impulses. Another well-cited theory in crowd psychology is *Emotional Contagion*,[4] where individuals in a large group can "catch" emotions from each other (Baig et al., 2014; Bertozzi et al., 2015; Bosse et al., 2013; Kim et al., 2021; Tsai et al., 2013). This can lead to a shared emotional experience, such as feeling a sense of euphoria or transcendence during a religious or sport gathering, or political rallies or an emergency situation (Berlonghi, 1995; Bishop et al., 2020; Soomaroo and Murray, 2012). Another well-cited and related theory is the *Interaction Ritual Theory* (Collins, 2014), developed by the sociologist Randall Collins. This theory aligns with Emotional Contagion and provides a model for understanding how transcendence and shared emotional experience occurs (through four ingredients) and with what outcomes. The theory has been applied to examine sport fan dynamics (Cottingham, 2012).

4. Crowd safety and crowd security, two interconnected but distinguishable notions

The terms *crowd safety* and *crowd security* are often used interchangeably. While they are inter-related notions, we argue here that there is a difference between the two (Wylde and Page, 2014). While both terms are related to managing large gatherings of people, they have distinct goals and approaches.

Crowd safety refers to the measures taken to ensure the physical safety and well-being of individuals within a crowd. It involves managing the flow of people to prevent overcrowding, ensuring that the venue or location is structurally sound and safe, providing adequate emergency medical services, and implementing crowd control measures to prevent accidents or injuries. Crowd safety measures also include the provision of emergency exits, clear signage, and trained personnel to assist with evacuations in case of emergencies.

Crowd security, on the other hand, refers to measures taken to protect

[3] Often, the people in the crowds whose protection should be ensured are not made of unrelated individuals, but have a feeling of belonging together, notably at sport events and religious festivals.

[4] It should be noted that The Contagion Theory is highly contentious among scholars, and we merely make reference to this theory this as a scientific point of view rather than a fact.

the crowd from external threats, including terrorism, crime, and violence. Ensuring Crowd Security is about protecting a crowd from harm caused by people with criminal or malicious intentions. A crowd security threat could come from an internal or an external source. For example, an internal security threat is that of sexual harassment of audience members at a festival. An example of an external threat could be a group of activists having the intention to disturb the event, thereby creating a dangerous situation. Crowd security measures include surveillance, the deployment of security personnel, and the implementation of access control measures. These measures are designed to prevent potential attacks, detect and respond to incidents quickly, and ensure the safety of everyone in the crowd. In other words, crowd safety focuses on the physical environment and ensuring that people are safe from accidents or incidents within the crowd. Whereas crowd security focuses on assessing threats from internal and external sources, managing these threats in the external environment and preventing and mitigating these threats from inside and outside the crowd. Both are critical to the successful management of large gatherings, and they work in unison to ensure that everyone is safe and secure. While this work touches on aspects related to both crowd safety and crowd security, the main focus here is on the former.

5. Definition of crowd management

Crowd management and crowd safety are both important aspects of event planning and management. The success of any event, whether it is a concert, sports game, festival, or political rally, depends on the ability of organisers to effectively manage the crowd, come up with timely and effective interventions and ensure their safety (Baxter et al., 2018; Earl et al., 2005; Emery, 2010; Martella et al., 2017; O'Toole, 2019; Wijermans et al., 2016). Crowd management is essential to prevent overcrowding, which can lead to accidents, injuries, and even fatalities (Abbott and Geddie, 2000; Hassanein et al., 2019). Overcrowding can occur when the number of people in a venue exceeds its capacity or when there are bottlenecks and chokepoints that prevent people from moving freely. Effective crowd management involves careful planning and organization, such as setting up barriers, entrances and exits, and managing the flow of people (Rahmat et al., 2011; Taibah and Arlikatti, 2015). By doing so, organisers can prevent overcrowding (Fourati et al., 2017), reduce the risk of accidents, and ensure that everyone has a good experience. Large crowds can be unpredictable and potentially dangerous, especially in situations where emotions are running high, such as at sport events or political rallies. Moreover, crowd safety is important not just for the attendees but also for the staff and performers. Ensuring that the crowd is managed effectively and safely can help to prevent staff and performers from feeling threatened or intimidated. In addition, ensuring good crowd management and safety can also have positive economic impacts by encouraging attendance in events and ultimately helping businesses associated with mass events. Moreover, good crowd management has links to the psychological wellbeing of both attendees as well as the personnel. For the people who experience being in a poorly managed crowd, the psychological trauma could be lasting and severe, even for those who do not suffer physical injuries. For example, as the press has documented, there have been reports of survivors committing suicide after the 2022 accident in Itaewon, South Korea,[5] and this also includes the security personnel.[6]

6. Stakeholders in crowd safety

The stakeholders of crowd safety include a range of individuals and organizations who have a direct or indirect interest in the safety and well-being of participants in crowds, including:

- *Event organisers*: Event organisers and facility operators are responsible for planning and managing events, including implementing crowd safety measures. They can work with practitioners to ensure that their events are safe and well-managed, and to develop effective crowd management strategies.
- *Emergency responders*: Emergency responders, including police, fire, and medical personnel, are responsible for responding to emergencies that occur in crowds. They can work with academics and practitioners to develop effective emergency response protocols and to ensure that they are well-prepared to respond to emergencies.
- *Security personnel*: Security personnel are responsible for maintaining order and ensuring the safety of participants in crowds. They can work with academics and practitioners to develop effective crowd control strategies and to ensure that participants are safe and secure (Earl et al., 2004a; Earl et al., 2004b; Hope et al.; Kingshott, 2014; Laws, 2016).
- *Government agencies*: Government agencies, including local, state, and federal agencies, have a role in regulating events and ensuring that they are safe for participants. They can work with academics and practitioners to develop and enforce safety regulations. They also provide support and resources for crowd safety research and practice. As part of the approval process they can review and question proposed crowd management plans.
- *Patrons*: Participants in crowds have a direct interest in their own safety and well-being, and they can play a role in ensuring that events are safe and well-managed.

It should be noted the above is only a selective and not exhaustive list of crowd safety stakeholders. Depending on the context, many other parties may become stakeholders in crowd safety and that can include venue operators, land owners, transport hub operators, and managers of cultural and touristic sites, to name a few.

7. Current challenges in crowd safety practice

One of the biggest challenges in crowd safety is the risk of crowd-related incidents. These incidents can include stampedes, crushes,[7] and collapses, and are often caused by overcrowding or insufficient crowd control measures. A crowd incident can be triggered by an external incident like a fire or a public order disturbance, but often there is no actual external incident that triggered the problem. In these cases, the gathering of too many people and the associated dynamics are enough to trigger the incident. Preventing these incidents requires effective crowd management, which involves managing crowd flow, controlling access points, and providing clear communication and guidance to attendees (Alaska et al., 2017).

A second challenge is to ensure the safety of crowd in emergencies. As mentioned, a fire can trigger certain crowd behaviour, which on itself can lead to more casualties. But also, not being able to escape in time from a direct threat because of the occupancy rate in a certain location, can result in large numbers of casualties. Often, rules for escape routes and escape times written down in law lack the specific characteristics of the crowd, the location, and the severity of the threat. Lack of understanding crowd behaviour can in these cases lead to purely theoretical calculations of width of emergency exits, not incorporating the way crowds will actually use these exits in a real incident. Related to this issue is the threat of terrorist attacks. Crowds are a prime target for terrorist attacks, as they offer a high concentration of people in a confined space. Protecting crowds from these threats requires effective

[5] https://koreajoongangdaily.joins.com/2022/12/14/national/socialAffairs/Korea-Itaewon-disaster/20221214172350250.html.

[6] https://www.bbc.com/news/world-asia-63594243.

[7] The subtle but important differences between the notions of "crush" and "stampede" in crowd science will be discussed later in the manuscript, under the major heading "Intrinsic risks to crowd safety".

security measures, including surveillance, screening, and security personnel (Hope et al., 2023) as well as efficient evacuation planning.

An intricate issue in crowd safety and management is the balance between security and privacy. In the effort to protect crowds from potential threats, security measures can sometimes infringe on individual privacy rights. It is essential to strike a balance between ensuring public safety and protecting individual privacy rights.

Inadequate collaboration between agencies and stakeholders currently poses another challenge to crowd safety practice. Effective crowd management for public events requires a better understanding between agencies (police, fire brigade, ambulance) and stakeholders (event organisers, crowd safety consultants, security) in order to have a cohesive and consistent control over crowd management systems. A better recognition of skills, resources and communication systems will improve crowd safety systems.

Another challenge in crowd safety and management is the rapid growth of social media and the challenges that this presents. Social media can be a valuable tool for gathering real-time information on crowd behaviour and sentiment, but it also presents new risks and challenges. For example, false information and rumours spread quickly on social media, and can cause uncertainty and confusion in crowds.

Finally, COVID-19 has presented new challenges in crowd safety and management (Haghani, 2022). There has been limited evidence for significant behavioural changes in crowds before and after the pandemic, bringing to question whether the conventional theories and practices that were in place prior to the pandemic are still going to be effective in a post-pandemic era.

8. Current knowledge gaps in crowd safety research and practice

Despite significant progress in crowd safety research and practice, there are still several knowledge gaps that need to be addressed including:

- *Understanding of complex crowd behaviour*: There is still much to learn about the psychological factors that influence crowd behaviour, particularly the emotional state of the crowd (Zhang et al., 2021), and how these factors can be managed to improve crowd safety (Sime, 1995; Wijermans et al., 2016). Although, it should also be noted that there are circumstances in which we may believe our inaccurate modelling estimates is arising from insufficient understanding of crowd psychology, whereas in reality, the problem could be stemming from a poor calibration of a physics-inspired model, which otherwise (if calibrated properly) may prove adequate (Haghani and Sarvi, 2017c, 2019c; Rzezonka et al., 2022).
- *Integration of new technologies*: There is a need for better integration of new technologies into crowd safety research and practice (Alabdulkarim et al., 2016; Sharma et al., 2018). While there have been some significant advances in technologies such as crowd simulation software and communication systems (Shao et al., 2019), there is still much to learn about how other forms of technologies can be effectively applied in real-world settings (Felemban et al., 2021; Noor, 2022). This is particularly the case when it comes to the deployment of Decision Support Systems (Martella et al., 2017; Van de Weghe et al., 2013; Wijermans et al., 2016) in crowd management practice.
- *Objective evaluation of the effectiveness of crowd safety measures*: While there are many different crowd safety measures that can be implemented, there is still a lack of research on their effectiveness. More research is needed to evaluate the effectiveness of different crowd safety measures and identify best practices. For this purpose, there is currently a clear need for developing standardised measures and metrics using which we can evaluate the level of perceived safety and satisfaction of patrons in a crowd (Karthika et al., 2022; Kendrick et al., 2012; Zanlungo et al., 2023). Criteria for objectively measuring the Level of Service in vehicular traffic do exist, but there is a clear gap in pedestrian traffic measures.
- *Understanding of cultural and social factors*: There is still much to learn about how cultural and social factors influence crowd behaviour and how these factors can be managed to improve crowd safety (Haghani, 2020a).
- *Collaboration and communication between different disciplines*: Effective crowd safety strategies require collaboration between different disciplines, such as psychology, computer science, engineering, and emergency management. There is still a need for better collaboration and communication between these disciplines to improve crowd safety research and practice. This is most distinct when it comes to collaborations between computer vision scientists and the mainstream crowd dynamics researchers (Albattah et al., 2020; Haghani, 2021; Yogameena and Nagananthini, 2017).

9. Risks to crowd safety

A safety risk is typically a potential undesired event, with a combination of a certain likelihood and a level of severity. In this sense, a low risk has both a low likelihood and severity, a mediocre risk has a high risk, or a higher severity and a high risk has both a high likelihood and a high severity. In the context of safety, the severity is often expressed in number of casualties and severity of injuries or the chance of deaths. Crowd safety risk refers to the likelihood or probability of harm or injury occurring to individuals or groups within a crowd or mass gathering (Dibley, 2023; Yang et al., 2022). It can arise from a range of factors, such as the number of people attending the event, the layout of the venue, the weather conditions, the behaviour of the crowd, and the actions of individuals or groups within the crowd (Subramanian and Verma, 2022).

Crowd safety risks can take various forms, including physical injuries, property damage, stampedes, violence, fire or explosion hazards, communicable diseases (Taibah et al., 2020), and other hazards that may arise from the interaction of large numbers of people in a confined space (Subramanian and Verma, 2022). The severity and likelihood of these risks can vary depending on the type of event, the size and composition of the crowd, and the specific circumstances of the gathering.

Effective crowd safety risk management involves identifying potential hazards and implementing appropriate measures to mitigate the risks (Davies, 1998; Ludvigsen, 2023; Ma et al., 2022; Silvers and O'Toole, 2020; Subramanian and Verma, 2022). This can include crowd control measures, emergency preparedness and response planning (O'Toole et al., 2019b, c; Soomaroo and Murray, 2012; Tsurushima, 2022), communication and coordination among stakeholders, and ongoing monitoring and evaluation of crowd safety risks. By managing crowd safety risks effectively, event organizers, emergency services, and other stakeholders can help ensure the safety and well-being of individuals within the crowd and minimize the potential for harm or injury.

9.1. The most significant safety risks to crowds

There are several significant safety risks to crowds in mass gatherings, including:

- *Crowd density and crush*: High crowd density and crush can lead to physical injuries and fatalities, especially in confined spaces or when there are sudden surges in crowd movement. This can occur in events such as concerts, sport events, or religious gatherings.
- *Stampedes*: Stampedes can occur when crowds suddenly rush towards certain points of egress or ingress, leading to physical injuries and fatalities. This can occur in events such as religious gatherings, sport events, or concerts with a highly competitive crowd, when the situation is not managed properly.

- *Cascading risks*: Where a minor incident causes a disproportionate reaction resulting in a stampede, crush or collapse of infrastructure.
- *Terrorism and violence*: Terrorist attacks and violence can pose a significant risk to crowds in mass gatherings. This can include bombings, shootings, or vehicular attacks. But also, acts of activists that aim to disturb an event to gain attention for their purpose, can have similar effects. The reaction of the crowd itself can instigate the risk of a crush or stampede. Also, the reaction of police forces to mitigate the threat can impose a risk to a crowd when the effects of police strategies on crowd safety are not understood.
- *Extreme weather*: Extreme weather conditions, such as heat waves or thunderstorms, can pose a risk to crowds in mass gatherings. This can lead to heat exhaustion, dehydration, or electrocution. In case of a downburst or overcast, crowds can suddenly move towards locations to take shelter, with the risk of a crush, overcrowding of a tent or other construction, compromising the options to escape from that location in case of an incident and the risk of being trapped when winds would bring the structure down. Lightning is a specific risk that is hard to mitigate at large events and in environments with little options to take shelter.
- *Structural issues*: Weak or poorly designed structures, such as bridges, balconies, and grandstands, can collapse under the weight of a large crowd, leading to injuries or fatalities. Sudden crowd movements and unexpected high load of a specific structure can instigate an incident. This can occur in events such as sport events with temporary stands,[8] in venues, at music festivals, at carnivals with large self-designed vehicles and at religious gatherings.
- *Fire and explosion hazards*: Fire and explosion hazards are a significant risk in events where there are large crowds and the use of pyrotechnics or flammable materials.
- *Communicable diseases*: Crowds in mass gatherings can increase the risk of spreading communicable diseases (Taibah et al., 2020). This can be especially challenging in events where social distancing and other preventive measures are difficult to enforce.

By conducting a thorough risk assessment, event organisers and authorities can determine which risks are reasonably foreseeable and what appropriate measures can be taken to prevent or mitigate these risks, such as implementing crowd control measures, increasing security measures, providing emergency response services, and educating the public on safety procedures (Baxter et al., 2018). Risk assessment also helps event organisers to comply with legal and regulatory requirements for crowd safety, such as building codes and health and safety regulations. It is an essential tool for ensuring that events are well-planned and well-executed, and that the safety of participants and the public is prioritised. A well-documented risk assessment can be proof that the person responsible for the safety of a crowd understood their responsibilities and duties of care. This may be important to get a permit or license, but also in case of an incident where accountability will be in place.

9.2. Crowd risk assessment

Assessing and measuring the risk to crowd safety involves a comprehensive approach that takes into account a range of factors that could impact the safety of individuals within a crowd. This includes risk assessment tools that can help identify potential safety risks and quantify the likelihood and severity of harm occurring (Reid and Ritchie, 2011; Sealy, 2020). These tools can involve both qualitative and quantitative methods, including surveys, observations, and statistical analysis (Au, 2001; Feliciani et al., 2022b, c; Menglong et al., 2012; Raineri, 2013; Yang et al., 2022):

- *Demographics:* At the core of crowd risk assessment is the demographic of the expected crowd and its configuration in age, gender and reasons for attending the event under review.
- *Crowd modelling:* Crowd modelling can be used to simulate crowd behaviour and movement, allowing for the identification of potential safety risks and the testing of various crowd management strategies. Crowd modelling can involve the use of computer simulations or physical models.
- *Environmental analysis:* An analysis of the environmental factors that could impact crowd safety, such as weather conditions, terrain, and access points, can help identify potential safety risks and inform the development of appropriate safety strategies.
- *Historical data analysis:* Historical data analysis can help identify patterns and trends in crowd safety incidents, allowing for the identification of potential safety risks as well as the potential demand for attendance, and the development of effective safety strategies.
- *Expert opinion:* Expert opinion from crowd safety professionals, emergency services, and other stakeholders can provide valuable insights into potential safety risks and inform the development of effective safety strategies.

9.3. Differentiation between intrinsic and extrinsic risk to crowd safety

Intrinsic risks to crowd safety are those that arise from the characteristics of the crowd itself, such as the behaviour and movements of individuals within the crowd. Examples of intrinsic risks to crowd safety include overcrowding, crushing, pushing, or stampeding, which can all occur due to the behaviour of individuals within the crowd. *Extrinsic risks* to crowd safety, on the other hand, are those that arise from external factors outside of the crowd, such as the venue, environmental conditions, or the actions of third parties. Examples of extrinsic risks to crowd safety include environmental hazards, such as extreme weather conditions or fires, as well as terrorist attacks or other acts of violence that may be directed towards the crowd. Both intrinsic and extrinsic risks to crowd safety can be significant, and it is essential to identify and manage them effectively to prevent harm or injury to individuals within the crowd (Feliciani and Nishinari, 2018). Effective and holistic crowd safety management involves a comprehensive and proactive approach to identifying potential risks, developing appropriate strategies to mitigate them, and ensuring effective communication and coordination among all stakeholders involved in the event (Feliciani et al., 2022b).

10. Extrinsic risks to crowd safety

10.1. Crowds as vulnerable entities to terrorism and violent attacks

Crowded spaces have always been a soft target for terrorist attacks and violent incidents. Places such as airports, train stations, shopping malls, and sport events attract large numbers of people, making them vulnerable to attacks (Spaaij, 2016). Crowded spaces present a challenge for security and emergency response, making it easier for terrorists to cause chaos and inflict casualties (Aradau, 2015; Dibley, 2023). Crowded places offer a high concentration of potential victims. The more people in a crowded space, the higher the likelihood of causing mass casualties. Terrorist organisations often seek to inflict maximum damage, and crowded spaces can become an ideal target.

Attacks on crowded spaces can be carried out in many ways, including bombings, shootings, and hostile vehicles (i.e., ramming) (Dezecache et al., 2021; Drury and Stott, 2011; Hess and Mandhan, 2022; Ilum, 2022; Jenkins and Butterworth, 2019; O'Toole et al., 2019d; Wang et al., 2019b; Williams et al., 2022). These methods allow terrorists to cause significant damage and spread fear among people. Moreover, the nature of crowded spaces, such as concerts or sport events, means that people may be less alert to their surroundings, making them easier targets (Cole et al., 2011).

Unfortunately, there have been numerous terror attacks in crowded

[8] An example of this would be The Heysel Stadium disaster in Belgium in 1985: https://en.wikipedia.org/wiki/Heysel_Stadium_disaster.

places around the world resulting in deaths and injuries (Bernardini and Quagliarini, 2021; van der Wal et al., 2021). Some examples of the most documented terror attacks in recent years include:

- Boston Marathon bombing in Boston, USA (2013): Two bombs exploded near the finish line of the Boston Marathon, killing three people and injuring over 260 others (D'Andrea et al., 2013; Griggs, 2017).
- Manchester Arena bombing in Manchester, UK (2017): A suicide bombing at an Ariana Grande concert killed 22 people, including children, and injured over 800 others (Baxter et al., 2018; Craigie et al., 2020).
- Barcelona attack in Barcelona, Spain (2017): A van was driven into a crowd in Las Ramblas, killing 14 people and injuring over 100 others (Bąk, 2022; Enjolras et al., 2019).
- Bataclan Theatre in Paris, France (2015): On the night of November 13, 2015, coordinated terror attacks across Paris left 130 people dead and 500 wounded (Arif et al., 2017; Bogacheva, 2016).
- Kunming attacks in China (2014): A group of 8 knife-wielding terrorists attacked passengers in the Kunming Railway Station, China, killing 31 people, and wounding 143 others (Wang et al., 2019b; Zhang et al., 2020b).

The psychological impact of an attack on crowded spaces is significant (Rubin and Wessely, 2013). Terrorist organizations seek to create an atmosphere of fear and instability in the population (Kiper and Sosis, 2015; Sinclair and Antonius, 2012). An attack on a crowded space can lead to injuries and loss of life. But it can also diminish the public's confidence in attending crowded places for years to come, thereby, causing significant economic and societal harm (Guttmann et al., 2021). The psychological impact of such an attack can last for years, and it can be challenging to restore the confidence of the public in the safety of crowded spaces (Enjolras et al., 2019; Hansen et al., 2016).

Addressing the vulnerabilities of crowded spaces when it comes to extrinsic risks such as terror attacks necessitates effective communication and coordination between security agencies and emergency services (Haghani et al., 2022). Regular training and exercises can help to test the effectiveness of the response system. At the same time, the role of community preparedness and training for the public should no longer be ignored (Haghani, 2020b). In parallel, measures should also be taken to ensure that surveillance and intelligence-gathering methods are in place. Authorities need to be vigilant in monitoring potential threats and suspicious activity around crowded spaces (Singh et al., 2020; Zhang et al., 2020a). The use of CCTV cameras, facial recognition technology, and other tools can aid in detecting potential threats, anomalies and identifying suspects (Feng et al., 2017; Mahadevan et al., 2010; Martella et al., 2017; Nishiyama, 2018; Sánchez et al., 2020; Yuan et al., 2014; Zitouni et al., 2016). Architects, event organisers and planners also need to incorporate security features such as bollards, barriers, and screening checkpoints into the design of crowded spaces (Chambers and Andrews, 2019; Ilum, 2022; Silberberg, 2013), while trying to preserve patron's mobility, accessibility and aesthetic satisfaction elements, especially with respect to the placement of bollards and protective barriers (Adams and Ward, 2020; Burns et al., 2021; Dorreboom and Barry, 2022; Tran et al., 2018). These measures can help to mitigate the impact of an attack and prevent vehicles from being used as weapons.

10.2. Martyn's Law: A new step toward making risk assessment a requirement

Related to extrinsic crowd risk management is *Martyn's Law*, a proposed piece of legislation in the United Kingdom that aims to improve the safety and security of public venues and spaces. The law, one of the only few items of legislation related to crowd and event safety (Davies, 1998; Laws, 2016; Walton, 2003), is named after Martyn Hett, one of the 22 people killed in the 2017 Manchester Arena bombing. This attack, which took place during a concert by Ariana Grande, highlighted the need for stronger security measures in public venues. It also brought attention to the fact that there were no specific requirements for the security of public spaces in the UK. Martyn's Law seeks to address this issue by introducing a set of minimum standards for venue security. The law would require all public venues and spaces to implement measures such as bag checks, metal detectors, and CCTV cameras can help to monitor the crowd and detect any unusual behaviour, allowing security personnel to respond quickly to potential threats. It would also require venues to carry out risk assessments and develop contingency plans in case of an emergency. The proposed legislation has received widespread support from various organizations and individuals, including Martyn's mother, Figen Murray, who has been campaigning for the law since her son's death. The UK government has also expressed its support for the law, with Home Secretary Priti Patel promising to introduce the legislation.

Martyn's Law will have major implications for venues. Currently, there is no standardisation in terms of venue security, with some venues having more comprehensive security measures than others. This can lead to a situation where some venues are seen as more attractive targets for attackers, simply because they are perceived as being less secure. Martyn's Law would ensure that all venues meet the same minimum standards, reducing the likelihood of attackers targeting specific venues.

Critics of Martyn's Law, on the other hand, have argued that it could be costly and burdensome for small venues, such as community centres and village halls. However, supporters of the law argue that the cost of implementing the minimum standards would be relatively low and that any costs would be outweighed by the potential benefits of improved security and saving lives.

It is expected that the implementation of Martyn's Law may face several practical challenges: (a) Implementing Martyn's Law will likely require additional financial resources to improve security measures and training. Many businesses and organisations may not have the budget to implement the necessary changes, which could slow down or prevent the implementation of Martyn's Law. (b) There may be a need to comply with various legal and regulatory requirements when implementing Martyn's Law. This could include obtaining permits and licenses for security measures, complying with data privacy laws, and ensuring compliance with health and safety regulations. (c) The implementation of Martyn's Law may require coordination between different agencies, organisations, and stakeholders. This could include local authorities, law enforcement agencies, businesses, and community groups. Ensuring effective communication and collaboration among these groups could be challenging. (d) The implementation of Martyn's Law will require the training of staff and stakeholders to ensure that they understand the requirements and are prepared to respond to potential threats. This could require additional resources and time and may be challenging to implement across a diverse range of businesses and organizations. (e) Resistance to change can also be a significant challenge when implementing Martyn's Law. Businesses and organizations may be resistant to implementing new security measures or procedures, especially if they do not see a direct benefit or if the changes are seen as disruptive to their operations.

11. Intrinsic risks to crowd safety

11.1. Crowd disasters as recurring phenomena around the world

Crowd crushes and crowd disasters are tragic events that can occur when large groups of people gather in one place while movement is restricted (Illiyas et al., 2013). These events can cause injuries and fatalities and are often the result of a combination of factors, including overcrowding, poor crowd management, and inadequate safety measures (Gayathri et al., 2017; Zhou et al., 2018). Different stages of such incidents include over-densification of crowds, trigger factors, and rescue failure (Huang and Jia, 2014). This can result in crushing injuries,

suffocation, and trampling, leading to fatalities. Unfortunately, there have been numerous crowd disasters throughout history that have resulted in significant loss of life and injury (Ball, 2007; Helbing and Mukerji, 2012; Krausz and Bauckhage, 2012; Sieben and Seyfried, 2023; Soomaroo and Murray, 2012). A more comprehensive database of such disasters can be found in Feliciani et al. (2023).

Over the last three decades, it is estimated that at minimum, 11,000 people have lost their lives in crowd disasters (Feliciani et al., 2023; Hsieh et al., 2009; Illiyas et al., 2013; Yamin, 2019). Some examples of major crowd disasters that have occurred in the recent years, to only list a few include[9]:

- Seoul Itaewon crowd crush: In October 2022 in the Itaewon neighbourhood of Seoul, South Korea during Halloween festivities with at least 159 casualties due to a crowd crush when huge numbers of revellers tried to enter the bar district form multiple directions, without any crowd management in place.
- Astroworld Festival crowd crush: in November 2021 in Houston, USA during Travis Scott's concert with 10 deaths and around 300 wounded, because of overcrowding on-site.
- Meron disaster: In April 2021 in Meron, Israel during an annual pilgrimage with 45 casualties, caused by a crowd crush on-site.
- Abidjan stadium disaster: in August 2020 in Abidjan, Ivory Coast before a FIFA World Cup match with 19 casualties.
- Kerman disaster: In January 2020, in Kerman, Iran during the funeral procession of a military person, with 56 casualties.
- Nairobi disaster: In February 2019, in Nairobi, Kenya, during a church service, with 15 casualties.
- Malang Kanjuhuran stadium disaster in Indonesia: in October 2022, with 135 deaths and almost 600 injured, when police forced a crowd to escape using tear gas.

Some of the most disastrous cases of such incidents include:

- Hajj accident (2015): During the annual Hajj pilgrimage in Mecca, Saudi Arabia, more than 2,400 people were killed and over 1,000 injured.
- Hillsborough disaster (1989): During an FA Cup semi-final match between Liverpool and Nottingham Forest, 96 people were killed and over 700 were injured because of a crowd crush inside the pens at the Hillsborough Stadium in Sheffield, England.
- Love Parade disaster (2010): During the Love Parade festival in Duisburg, Germany, 21 people were killed and over 500 injured because of a crowd crush in the queues towards the festival site.
- Mina stampede (1990): During the annual Hajj pilgrimage in Mina, Saudi Arabia, more than 1,400 people were killed and over 1,000 injured.
- Kumbh Mela stampede (2013): During the Hindu festival of Kumbh Mela in Allahabad, India, at least 36 people were killed and dozens more were injured.
- The Station nightclub fire (2003): A fire in a nightclub in West Warwick, Rhode Island, 100 people were killed and over 200 were injured when they tried to escape through a narrow exit when pyrotechnics had set the place on fire.
- Ellis Park Stadium disaster (2001): During a soccer match between South Africa and Zimbabwe at Ellis Park Stadium in Johannesburg, South Africa, 43 people were killed and over 150 were injured.

11.2. Crowd crush, crowd instability, turbulence and stampede

There is a difference between *crowd crush* and *crowd stampede*, even though these terms are often used interchangeably, particularly by the media (Feliciani et al., 2023; Lügering et al., 2023). Crowd crush occurs when people are crushed or squeezed. This can happen in situations where there are too many people in a confined space, or where there are obstacles that prevent the free flow of people. In a crowd crush, people are typically immobilised, and it becomes challenging for them to move. On the other hand, a crowd stampede is a sudden, uncontrolled movement of people, usually caused by uncontrolled fear or excitement (Alaska et al., 2017; Hsieh et al., 2009; Ngai et al., 2009). Stampedes often occur when there is a perceived threat or danger, such as a fire or an attack, and people try to escape or move away from the danger as quickly as possible. In a stampede, people move in an unpredictable manner, and it becomes difficult to anticipate their movements or control the situation, leading to trampling and crushing injuries.

Linked to crowd crushes are crowd *turbulence* and *instability* (sometimes also referred to as *crowd quakes* (Ma et al., 2015)).[10] They are complex phenomena that can occur in large groups of people (Golas et al., 2014; Helbing et al., 2007; Ivancevic and Reid, 2012; Wang et al., 2019a). Fundamentally, crowd turbulence and instability is associated with the fluid-like behaviour of the crowd (Jiayue et al., 2014). In a normal crowd, individuals move in a coordinated manner, with each person adjusting their movement based on the movement of those around them. However, when the density of the crowd exceeds a certain threshold, the fluid-like behaviour can break down, leading to turbulence and instability (Haghani and Lovreglio, 2022). This can particularly occur when dense crowds confront bottlenecks or obstructions.

12. The role of legislation and policy in crowd safety

Authorities have the duty to take care of public safety and security. This also involves ensuring the safety of public events and other crowded places. To do so, there are systems in place that in most countries are based on permitting or licensing the person or organisation responsible for the utilisation of a location or activity. Legislation, permits, licenses and policy play a crucial role in ensuring crowd safety. They provide a legal framework that outlines the responsibilities of event organisers, authorities, and other stakeholders in ensuring the safety of crowds. They are crucial to clarify who is responsible where (i.e., event location, private property, public area in front of the venue, etc). Legislation and policy on crowd safety typically cover a range of areas, including building codes, fire safety, health and safety regulations, and emergency response procedures. They may also include requirements for crowd management, crowd control, and crowd dispersal. One of the key roles of legislation and policy is to establish minimum safety standards that must be met by event organisers and authorities. This includes requirements for the number and placement of exits, fire safety equipment, crowd control measures, and emergency response plan and procedures (Abbott and Geddie, 2000; Laws, 2016; Tum and Norton, 2006). In permits, (often local) authorities can add specific requirements to a location or activity, that are tailor-made or typical for the city, environment, or type of activity for which the permit is being granted. This gives authorities the possibility to demand more than the minimum requirements that come from law. Guidelines can be a source for these requirements, but they can also be developed locally and thus differ across geographical locations.

Legislation and policy also play a role in promoting best practices in crowd safety. They may require event organizers to undergo training and certification in crowd management or establish guidelines and recommendations for crowd control and emergency response. Moreover, legislation and policy can provide a means of accountability for event organizers and authorities (Abbott and Geddie, 2000; Khir et al., 2019; Mahoney et al., 2015; Praznik et al., 2020). They may establish penalties for non-compliance with safety requirements and provide a

[9] https://www.theguardian.com/world/2022/oct/29/the-deadliest-crowd-crushes-of-the-last-decade.

[10] https://www.science.org/content/article/what-causes-deadly-crowd-quakes.

mechanism for investigating incidents and holding individuals or organisations responsible for any harm caused to the public.

There are a few existing pieces of legislation and/or guidelines[11] that relate (directly or indirectly) to crowd safety, which may vary depending on the country or region. Examples include *The Safety at Sports Grounds Act 1975 (UK)* also known as the Green Guide, regulates safety at sports grounds in the UK, including the safety of spectators. It requires sports grounds to be licensed and sets out safety standards that must be met. Another example is *The Event Safety Guide*[12]: This guide provides information and guidance on safety planning and risk management for events, including events that involve crowds. It sets out safety standards and requirements that must be met.

13. The role of technology in crowd safety

13.1. The role of AI and computer vision in crowd safety

With the rapid advancement of technology, *artificial intelligence* (AI) and *computer vision* (CV) have emerged as promising tools to aid crowd management (Almutairi et al., 2022; Martella et al., 2017; Sharma et al., 2018; Tatrai, 2021; Yogameena and Nagananthini, 2017). AI and CV can also be used to predict crowd behaviour and anticipate potential crowd-related incidents. These systems can analyse historical data on crowd behaviour and use machine learning algorithms to identify patterns and trends (Islam et al., 2019). This can help to identify potential risks and enable proactive measures to be taken before an incident occurs (Bamaqa et al., 2022; Constantino et al., 2020).

One of the main applications of AI and CV in crowd management is crowd monitoring (Davies et al., 1995; Singh et al., 2021) including the detection of *anomalies* and *abnormal behaviour* (Afiq et al., 2019; Chen and Lai, 2019; Feng et al., 2017; Wang and Xu, 2016). AI and CV systems can be used to analyse real-time video feeds from surveillance cameras to detect and track movements in the crowd. These systems can be programmed to recognise specific behaviours, such as aggression, fighting, or suspicious activity, and alert security personnel accordingly (Alzahrani et al., 2020; Baliniskite et al., 2019; Saba, 2021; Sultani et al., 2018). This can help to prevent incidents before they escalate, and provide real-time situational awareness to security personnel.

Another application of AI and CV in crowd management is crowd counting and density estimation. AI can help manage crowd flow by analysing crowd movement and predicting crowd density in specific areas (Li et al., 2021; Sindagi and Patel, 2018; Zhang et al., 2015). This information can be used to optimize the flow of people through various checkpoints and entrances, reducing overcrowding and preventing stampedes.

Additionally, AI and CV can be used to optimise crowd control measures. For example, AI-powered *decision support systems* (Martella et al., 2017; Van de Weghe et al., 2013; Wijermans et al., 2016) can be used to monitor the effectiveness of control measures and make real-time adjustments to improve crowd flow and safety. Moreover, in the event of an emergency, AI can help direct people to safety by providing real-time information on the location of exits, emergency services, and evacuation routes (Lopez-Carmona, 2022; Lopez-Carmona and Garcia, 2021; Lopez-Carmona and Paricio-Garcia, 2020). This information can be communicated via mobile apps or public address systems or visual information systems, enabling people to quickly and safely evacuate.

Crowd monitoring and control is an important aspect of ensuring public safety at events and in crowded public spaces. However, it is equally important to protect the *privacy* of individuals who are being monitored (Bittau et al., 2017; Chan et al., 2008; Stanciu et al., 2021). Privacy is widely regarded as a fundamental human right. Individuals have the right to privacy and to control their personal data, including their movements and activities in public spaces. Crowd monitoring and control measures should be designed to protect the privacy of individuals, while also ensuring public safety. Secondly, the use of surveillance technology can be invasive and intimidating. When individuals are aware that they are being monitored, it can create an effect on their behaviour, experience and activities, leading to self-censorship and a restriction of individual freedoms. This can have a negative impact on social and cultural life, as people may be less likely to attend events or engage in public activities if they feel that their privacy is being violated.

There is also a risk of misuse or abuse of surveillance technology. In some cases, surveillance technology has been used to target specific individuals or groups, leading to discrimination and marginalisation. Additionally, surveillance technology can be vulnerable to hacking and data breaches, leading to the exposure of personal information and compromising the privacy of individuals (Costin, 2016; Samonte et al., 2022). To protect privacy in crowd monitoring and control, it is important to adopt a *privacy-by-design* approach (Erkin et al., 2014; Klitou, 2014; Pagallo, 2021; Rosen, 2004). This involves considering privacy implications from the outset and designing measures to minimise privacy risks. This can include measures such as data minimisation, encryption, and anonymisation. Additionally, transparency and accountability are key in protecting privacy (Imran et al., 2017). Individuals should be informed about the use of surveillance technology and how their personal data will be collected, stored, and used (d'Aquin et al., 2018). Furthermore, there should be clear guidelines and oversight mechanisms in place to ensure that surveillance technology is used in a responsible and ethical manner.

13.2. The role of sensors in crowd safety

Sensors (to be intended in broad sense as any sort of measuring device) can play a critical role in crowd safety by providing real-time data and information that can be used to monitor crowds, detect potential safety risks, and respond quickly to emergencies (Ramesh et al., 2014; Wirz et al., 2013; Yamin, 2019). Sensor technology could be used to (i) monitor crowd behaviour and movement patterns, including crowd density, speed, and direction. This information can be used to detect potential safety risks, such as overcrowding, and to plan for effective crowd management strategies, (ii) monitor environmental factors that may affect crowd safety, such as temperature, humidity, and air quality. This information can be potentially integrated with *Decision Support Systems* and be used to make decisions about crowd management and emergency response, such as when to provide additional water or cooling stations for participants, (iii) detect safety/security hazards in the crowd, such as smoke or fire. They can also detect other safety risks, such as the presence of hazardous materials or suspicious behaviour, (iv) trigger automatic responses in the event of an emergency, such as alerting emergency responders or triggering emergency alarms.

13.3. The role of social media monitoring in crowd safety

Social media could offer an emerging and valuable source of information and a tool for crowd management and event safety (Rothschild, 2011). Social media platforms like Twitter and TikTok have millions of users who share real-time updates and information about events and crowd behaviour. One of the primary applications of social media monitoring is *real-time situational awareness* (Gong et al., 2020; Martella et al., 2017). By monitoring social media feeds, security personnel and event organizers can gain valuable insights into crowd *behaviour* and

[11] Here, we need to stress the distinction between legislation and guidelines in this context, in that, the status of guidelines may differ very much, and in most cases, they are not directly enforced by law.

[12] The Event Safety Guide is an American publication prepared by the Event Safety Alliance. There have been different attempts to write event safety guidelines in Australia, notably the Event Safety Resource Guide and the LPA (Live Performance Australia) Safety Guidelines but none are legislative documents and could be used as guides only.

sentiment (Cai, 2013; Gong et al., 2019; Roberts et al., 2019; Singh et al., 2019; Wakamiya et al., 2015). Social media monitoring can help identify potential threats and risks and enable proactive measures to be taken to prevent incidents before they escalate. Another application of social media monitoring is *crowd counting* and tracking. By analysing social media posts and geotags, organisers can estimate the number of people attending an event (Gong et al., 2021; Gong et al., 2018). This can help to prevent overcrowding and congestion, which are significant risk factors for crowd-related incidents. Social media monitoring can also be used to identify and *respond to incidents in real-time* (Beigi et al., 2016; Ngo et al., 2016). By monitoring social media feeds, security personnel can quickly identify incidents and dispatch personnel to respond. Social media monitoring can also help to coordinate response efforts and provide real-time updates to the public. Additionally, social media monitoring can be used to identify potential threats and risks before an event. By analysing social media feeds, organisers can identify trends and patterns that may indicate potential security threats. This can help to inform security planning and enable proactive measures to be taken to prevent incidents before they occur.

13.4. The role of computer simulation in crowd safety

Computer simulation models can also play an important role in improving crowd safety by allowing planners and designers to test and optimise crowd management strategies in a controlled, virtual environment (Haghani, 2020b). This includes:

- *Predictive Analysis*: Simulation models can be used to predict the behaviour of crowds in different scenarios, allowing planners to identify potential risks and develop appropriate mitigation strategies. For example, simulation models can be used to predict crowd density and flow, helping to identify potential bottlenecks or overcrowding that could lead to accidents (Gödel et al., 2020; Kurtc et al., 2021; Yu and Johansson, 2007).
- *Testing Emergency Response Plans*: Simulation models can be used to test emergency response plans in a safe and controlled environment. This can help identify potential weaknesses in the plan and allow for adjustments to be made before a real emergency occurs (Haghani and Sarvi, 2023; Lovreglio et al., 2016).
- *Optimising Crowd Management Strategies and Design*: Simulation models can be used to test different crowd management strategies, such as the location of entry and exit points, the placement of barriers, and the deployment of security personnel. This can help to optimise these strategies and identify the most effective approach for managing crowds in different scenarios (Abdelghany et al., 2010; Abdelghany et al., 2014; Haghani, 2020b; Lopez-Carmona, 2022; Lopez-Carmona and Paricio-Garcia, 2020; Verbas et al., 2016).
- *Training Personnel*: Simulation models can also be potentially used to train personnel in crowd management and emergency response procedures. This can allow personnel to gain practical experience in a controlled environment and develop the skills needed to respond effectively in a real emergency (García-García et al., 2012; Kim et al., 2016b).

Although computer simulation models have become an increasingly popular tool for studying crowd dynamics and predicting potential safety issues in mass gatherings, there are several practical challenges and issues that need to be addressed when using these models for crowd safety purposes. One major challenge is the need for accurate data to input into the models. Accurate information on the characteristics of the crowd, such as demographics, behaviour, and movement patterns, is crucial to generating realistic simulations (Haghani et al., 2019b). However, gathering this data can be difficult, particularly for large-scale events. Another challenge is the complexity of the models themselves. Crowds can be inherently unpredictable and subject to sudden changes in behaviour, making it difficult to accurately model their movements and interactions. As a result, simulation models may be limited in their ability to accurately predict potential safety issues or provide guidance on effective safety measures. Moreover, the effectiveness of simulation models can be impacted by the assumptions and limitations of the models as well as the accuracy of their parameter settings (Haghani and Sarvi, 2023; Wang et al., 2021). The accuracy and reliability of models can be limited by factors such as the quality of data input, the assumptions made about crowd behaviour, and the limitations of the technology used. The key message here to utilise capabilities of simulation models for planning and training purposes, while also being aware of the limitations. This goes for both developers and end users of simulation models, although the developers have the responsibility to continuously monitor, discover, and mitigate these limitations. This is a particular area where communication between academics and commercial model developers could play a key part. Detailed guidelines with respect to data, the source, method of input and interpretation will be required to make computer simulations a more acceptable prediction tool.

14. The role of soft measures and behavioural interventions in crowd safety

14.1. The notion of public awareness and safety culture

Public awareness, educational campaigns, and safety culture can play a significant role in enhancing crowd safety, although their potential in that space is so far highly underexplored. Here are some ways in which they can help:

- *Improved Awareness & Education*: Public awareness campaigns can help people understand the risks and dangers associated with crowded places and events. By making people aware of the potential risks and dangers, they can take appropriate measures to protect themselves and others. Educational campaigns can provide people with the knowledge and skills they need to respond appropriately in the event of an emergency. This can include training in first aid, crowd safety, and evacuation procedures and best evacuation strategies (Haghani and Sarvi, 2019a, d, e; Haghani et al., 2019b).
- *Crowd Management Strategies*: Safety culture can promote good crowd management practices such as effective crowd control measures, crowd flow management, and emergency response planning. By promoting a safety culture, people can learn to take responsibility for their own safety and help to ensure the safety of others in crowded places. Educating the public about crowd management strategies can also help reduce the risk of crowd disasters. This can include information about how to move safely within a crowd, how to recognize and respond to crowd pressure, and how to follow instructions from emergency services.
- *Risk Mitigation*: Safety culture can promote a proactive approach to risk mitigation, encouraging people to identify potential hazards and take appropriate measures to minimise the risk of harm at their personal level.
- *Communication of Safety Information*: Effective communication is key to crowd safety. Communication is essential in providing detailed information to the crowd at the point they need specific guidance to avoid an emergency. Public awareness campaigns can help people understand the importance of clear communication during an emergency. This can include the use of public address systems, mobile apps, and social media to provide real-time information on the location of exits, emergency services, and evacuation routes (Lopez-Carmona, 2022; Lopez-Carmona and Garcia, 2021; Lopez-Carmona and Paricio-Garcia, 2020; Ran et al., 2014).
- *Pre-event Planning*: Encouraging individuals to plan ahead before attending a mass gathering is another effective way to prevent crowd disasters. This can include preparing for extreme weather conditions,

identifying emergency exits and evacuation routes, and knowing how to reach emergency services.
- *Responsible and altruistic Behaviour*: Encouraging responsible behaviour within the crowd can also help prevent crowd disasters. This can include reminding individuals to avoid excessive alcohol consumption, follow public health guidelines, respect the rights of others within the crowd, encourage fellow patrons to do the right thing and adopt the right strategies, and to render assistance to injured individuals during emergencies.

Providing crowd safety awareness at a community level means educating individuals, organisations, and groups within a community about the potential risks and hazards associated with large crowds or events. This may involve providing information about emergency protocols, crowd control measures, and other safety procedures that can be implemented to prevent injuries or incidents during large gatherings. The goal of crowd safety awareness is to empower members of a community to recognise potential safety hazards and to take appropriate action to mitigate them. This may involve providing training to volunteers, event organisers, and emergency responders, as well as disseminating information about safety procedures and protocols to members of the community. Overall, providing crowd safety awareness at a community level is an important way to help ensure the safety and well-being of individuals attending events or gatherings, while also promoting a culture of preparedness and resilience within the community as a whole.

14.2. Avenues and barriers of crowd safety behavioural campaigns

There are several effective avenues for educating the public on crowd safety, including:

- *Social media*: Social media is an effective tool for sharing information about crowd safety, as it allows for the dissemination of information to a wide audience quickly and easily. Social media platforms such as Twitter, Facebook, and Instagram can be used to share safety tips and guidelines, and to engage with the public about crowd safety.[13]
- *Mass media*: Traditional mass media such as television, radio, and newspapers are also effective channels for educating the public on crowd safety. News outlets can report on crowd safety incidents and provide information on how to stay safe during mass gatherings.
- *Mobile applications*: Mobile applications that provide real-time information about crowd safety can be effective in educating the public. These applications can provide safety tips, real-time alerts, and maps that show the location of medical facilities and emergency exits.
- *Public events and workshops*: Public events and workshops can be used to educate the public on crowd safety. These events can provide interactive learning opportunities, allowing individuals to ask questions and receive hands-on training.
- *Public signage*: Signage can be used to communicate safety messages to the public, such as warning signs, directional signs, and safety guidelines. Signage should be clear and concise, using universal symbols and plain language.
- *Partnerships with event organisers and community organizations*: Partnerships with event organizers and community organisations can be used to promote crowd safety. These partnerships can involve the development of educational materials and the distribution of safety information.

By using a range of educational avenues, stakeholders can reach a wide audience and increase awareness of crowd safety (Alaska et al., 2017). *School education* is also particularly an effective avenue for promoting crowd safety. Educating students about crowd safety can help to instil safe behaviours at a young age and promote lifelong habits of safety consciousness and spread the knowledge within the families and communities (Bahmani et al., 2023; Chen et al., 2019; Ding et al., 2021). In other words, school students can play the role of *knowledge vectors* in the context of safety campaigns. Here are some ways that schools can educate students on crowd safety:

- *Curriculum integration*: Crowd safety can be integrated into the curriculum in subjects such as health, physical education, and social studies. This integration can help make crowd safety become part of a broader package of safety training in schools and provide students with the knowledge and skills needed to stay safe during mass gatherings.
- *Guest speakers*: Guest speakers such as emergency service providers and community leaders can be invited to schools to speak about crowd safety. These speakers can provide real-life examples and share their experiences to help students understand the importance of crowd safety.
- *Assemblies and events*: School assemblies and events can be used to educate students about crowd safety. These events can provide interactive learning opportunities, allowing students to ask questions and receive hands-on training.
- *Safety drills*: Schools can conduct crowd safety drills to help students understand what to do in the event of an emergency. These drills can be used to practice evacuations, safety procedures, and other safety measures.
- *Educational materials*: Schools can provide educational materials such as posters, brochures, and videos that promote crowd safety. These materials can be displayed in common areas, classrooms, and other areas of the school.

Educating the public for crowd safety can be challenging due to a range of practical factors:

- *Reaching the target audience*: Reaching the target audience with the necessary information can be difficult, especially if they are not aware of the potential risks. The message may not reach those who need it most, or they may not take the necessary precautions.
- *Limited resources*: Resources such as funding, staff, and time may be limited, making it challenging to reach a wide audience effectively.
- *Time constraints*: Information about crowd safety must be provided in a timely manner before the event. This means that educational materials must be created and distributed before the event, which can be a challenge due to tight timelines. Information must be repeated on-site in a manner consistent with the information provided before the event.
- *Resistance to change*: Some members of the public may be resistant to change and may not want to change their behaviour. It can be difficult to convince some people to adopt new behaviours that promote crowd safety.
- *Compliance*: Even if the public is aware of the potential risks and how to stay safe, there may be a lack of compliance with safety guidelines, such as following crowd management strategies or avoiding risky behaviour.

Overall, educating the public for crowd safety requires a comprehensive approach that addresses the practical challenges mentioned above. Strategies to overcome these challenges include using multiple communication channels, creating culturally sensitive educational materials, working with community organisations, and engaging with event organizers and emergency services, and recognising the fact that, in many cases, in order to avert crowd disasters, not 100% of the crowd members need to have been educated and/or trained. With respect to

[13] Efforts should be made to warrant the scientific reliability of the advice communicated on these platforms, for instance by making sure that they originate from trustworthy sources.

certain aspects of behaviour, there is evidence suggesting that a concentration of about 50%-60% trained individuals within the crowd would achieve near-maximal benefit, comparable to that of a crowd of fully trained individuals (Haghani and Sarvi, 2019a). Furthermore, it should also be noted that a comprehensive training program should encapsulate aspects related to both intrinsic and extrinsic risks to safety.

14.3. How crowd safety preparedness can be measured

Objective measurement of crowd safety preparedness requires development of customised and standardised scales. Developing a measurement scale to assess individuals' crowd safety preparedness level requires a systematic approach. Some general steps that could be followed are:

1. Conduct a thorough review of the literature to identify existing measurement scales related to crowd safety preparedness or similar constructs. This will help in identifying the key domains and indicators to be included in the new measurement scale.
2. Develop a pool of items based on the identified domains and indicators. The items should be written in clear and concise language and should cover a range of levels of preparedness.
3. Administer the pool of items to a sample of individuals who are representative of the population of interest (e.g., attendees of large events). Use statistical techniques such as factor analysis to identify the underlying factors that explain the variation in responses to the items.
4. Refine the measurement scale by eliminating items that do not contribute to the identified factors or that have low reliability. The resulting scale should have good psychometric properties, including high reliability and validity.
5. Use the final measurement scale to assess individuals' crowd safety preparedness level in various settings, such as before and after attending large events, or in the context of emergency preparedness training.

The main applications of such scales could include (a) assessing the effectiveness of crowd safety interventions, such as safety briefings or evacuation drills, by measuring changes in individuals' preparedness level over time. (b) Identifying individuals and/or communities who may need additional crowd safety training or support to improve their preparedness level. (c) Comparing the preparedness level of individuals across different demographic groups, such as age, gender, or education level, to identify potential disparities and inform targeted interventions.

There is a limited amount of research on the development of measurement scales specifically designed to assess individuals' crowd safety preparedness level. While there are some existing measurement scales related to disaster preparedness or emergency response, they do not focus specifically on crowd safety preparedness (Boylan and Lawrence, 2020a, b; Every et al., 2019; Goh and Tandoc, 2022; Zsido et al., 2020). Therefore, it can be concluded that there is a knowledge gap regarding the development of a comprehensive measurement scale that specifically assesses individuals' crowd safety preparedness level (for both intrinsic and extrinsic risks). Further research is needed to develop and validate such scales to improve crowd safety management as well as emergency preparedness planning.

14.4. The role of nudging and subtle interventions

Behavioural nudging methods, which involve making small changes in the environment or context to influence behaviour, can play a role in crowd management and crowd safety practices, as a method whose potential in this space is still largely untapped.

Nudging involves the use of subtle interventions to influence the behaviour of individuals within a crowd or mass gathering (Feliciani et al., 2022a; Sieben et al., 2017). This can involve simple changes to the physical environment, such as the placement of signage or barriers, or the use of social norms and messaging to encourage positive behaviours and discourage negative behaviours (Buikstra, 2021). Nudging can be effective in managing crowds because it does not rely on the use of force or coercion and can be less disruptive than traditional crowd control measures. By providing gentle cues or reminders, nudging can encourage individuals within a crowd to behave in a particular way, such as moving in a particular direction or adhering to social distancing guidelines. However, nudging should not be seen as a standalone crowd management technique, and it should be used in conjunction with other strategies to manage crowd safety risks effectively. For example, nudging may be most effective when used alongside other measures, such as crowd control barriers, emergency preparedness planning, and effective communication and coordination among stakeholders. Overall, nudging can be an effective tool in managing crowds, but it should be used as part of a broader approach to crowd safety and management, which takes into account the specific needs and risks of the event or venue.

14.5. The notion of "zero responders" in crowd emergencies

Zero responders (or alternatively, *initial responders*) are individuals who are not trained emergency responders, but who are present at the scene of an emergency. In a crowd emergency, these individuals can become helpful in mitigating the harm by providing immediate assistance until trained emergency responders arrive (Ashkenazi and Hunt, 2019; Bartolucci and Magni, 2016; Cocking, 2013; Cole et al., 2011). Here are some ways that "zero responders" can be helpful in a crowd emergency:

- *Alerting emergency services*: they can call emergency services, such as the police, fire department, or ambulance, to report the emergency and request assistance. This immediate notification can help to ensure that trained emergency responders arrive on the scene as quickly as possible.
- *Providing first aid*: zero responders can provide first aid to injured individuals, such as applying pressure to a wound or performing CPR. This immediate assistance can help to stabilize the injured person until emergency responders arrive.
- *Assisting with evacuations*: they can assist with the orderly evacuation of the crowd by directing individuals to emergency exits and helping to clear pathways. This assistance can help to prevent overcrowding, which can lead to further injuries.
- *Providing comfort and support*: they can provide comfort and support to individuals who are experiencing shock or emotional distress. This support can help to calm individuals and prevent fear from spreading throughout the crowd.

As crowd safety educational campaigns are adopted and achieve effective levels of penetration within the society, it will become more likely that zero responders are present within crowds and mass gatherings, who can help avert a disaster before unfolding or help mitigate its effect.

15. Further contemporary topics in crowd safety research and practice

15.1. Misbeliefs, misconceptions, and fallacies about crowd behaviour

Misbeliefs, misconceptions, and fallacies about crowd behaviour have often influenced crowd management practices, sometimes leading to ineffective or even dangerous approaches to crowd control. Here are some common examples:

- *Panic is the main cause of crowd disasters*: The belief that panic is the primary cause of crowd disasters has led to the use of forceful crowd

control measures, such as pushing or shoving, which can actually increase the risk of injury or death (Clarke, 2002; Johnson, 1987; Keating, 1982; Norwood, 2005; Ouellette, 2019; Sheppard et al., 2006). In reality, crowd disasters are often caused by a combination of factors, including crowd density, infrastructure design, and communication breakdowns. "Panic" (or, more precisely, the emergence of very nervous behaviour and possibly incoherent actions detrimental to the group) could be associated with crowd disasters, but it is usually a consequence of them and not the cause.

- *Crowds are irrational and uncontrollable*: This misconception can lead to a perception that crowds are inherently dangerous and that they cannot be managed without the use of force (Haghani et al., 2019a; Lügering et al., 2023). However, research has shown that crowds can be highly organised and cooperative (Alnabulsi et al., 2018; Drury et al., 2019; Drury et al., 2009b), and that effective crowd management strategies can help prevent incidents.
- *Crowds behave as a single entity*: This fallacy assumes that individuals in a crowd generally act in a uniform and coordinated manner, as they do in specific circumstances, such as marathon starting corrals (Bain and Bartolo, 2019). In reality, crowd behaviour is often highly diverse and can be influenced by a range of individual factors, including emotions, intentions, and social dynamics (Bellomo et al., 2022; Bellomo et al., 2023). A crowd may appear as a uniform entity if observed from a distance, but this results from complex and diverse interactions occurring between the individuals within that crowd.
- *Crowds are homogenous*: Along the same line as the above, it is often not justified to assume that crowds are composed of people who are all the same in terms of demographics, behaviour, and intentions (Bain and Bartolo, 2019; Ouellette, 2019). In reality, crowds can be highly diverse, including individuals with different ages, genders, cultural backgrounds, and motivations, personality traits, beliefs and attitudes (Haghani and Sarvi, 2016b, 2017b). Crowds do attempt to achieve a uniform behaviour, but this arises because a collective identity is typically sought and not because individuals are homogeneous from the very beginning.
- *Crowd control measures are always necessary*: This belief assumes that aggressive crowd control measures are always necessary to prevent incidents. However, research has shown that effective communication, cooperation, and coordination between organisers and attendees can often be more effective at ensuring crowd safety (Bartolucci and Magni, 2016).

Overall, these misbeliefs, misconceptions, and fallacies can lead to ineffective or even dangerous and counter-productive approaches to crowd management. Understanding the realities of crowd behaviour and adopting evidence-based strategies can help prevent incidents and ensure the safety of attendees.

15.2. How we can learn from near misses

Near miss incidents in crowd management can provide valuable learning opportunities to prevent future crowd disasters. Near misses are incidents that could have resulted in harm or injury but were avoided due to timely intervention or luck (Jones et al., 1999). Learning from these incidents can help identify potential hazards and improve crowd management practices to prevent similar incidents from occurring in the future.

One way to learn from near misses is to conduct a detailed analysis of the incident. This involves gathering information on the event, the crowd, and the management strategies that were in place. The analysis should identify the factors that contributed to the near miss and assess the effectiveness of the crowd management strategies that were employed. The analysis can then be used to develop and implement new strategies to prevent similar incidents in the future. For example, if the near miss was due to overcrowding, the event organisers can increase the number of entry and exit points, improve signage, and adjust the capacity of the venue. If the near miss was due to communication breakdown, organisers can improve communication channels between staff and attendees, or use technology to facilitate better communication. Another way to learn from near misses is to involve stakeholders in the analysis and decision-making process. This includes event organisers, emergency responders, and attendees. By involving all stakeholders, a more comprehensive understanding of the incident can be achieved, and a wider range of perspectives can be taken into account. Finally, it is important to foster a working environment where near misses are not treated as failures, but as a learning opportunity. Very often information on near misses is not shared or only within a given organisation. Small organisations or people with less experience may therefore lack access to this important source of experience.[14]

15.3. The need for objectives scales, indexes & measurement criteria

To improve crowd safety practices, it may also be helpful to measure the *level of service* and *satisfaction* of attendees (Cheng et al., 2021; Filingeri et al., 2017, 2018; Kendrick et al., 2012; Kim et al., 2016a; Yang and Lam, 2020; Zanlungo et al., 2023). There are potentially several objective ways to measure the level of service and/or satisfaction of people in crowds and mass gatherings. One common method is to use surveys or questionnaires to gather feedback from attendees on their experience. These surveys can ask attendees to rate various aspects of the event, such as the availability of facilities, the quality of entertainment, or the ease of navigation (Karthika et al., 2022; Ma et al., 2022). An alternative way to measure service level and satisfaction is through the use of metrics such as *wait times*, *crowd density*, and *flow rates* (Subramanian and Verma, 2022). These metrics can be monitored using technology such as cameras, sensors, and tracking systems. By analysing the data collected, event organisers can identify areas where improvements can be made to enhance the attendee experience. Furthermore, social media and online review platforms can also provide valuable insights into the level of service and satisfaction of people in crowds and mass gatherings. Attendees often share their experiences on these platforms, which can provide event organisers with feedback and areas for improvement. Overall, while measuring the level of service and satisfaction of people in crowds and mass gatherings can be challenging, there are potential objective ways to do so. Cameras and sensors can be also used to gain more subtle information less related to the crude head count. For example, applications include tracking facial expressions, body language, and other nonverbal cues to detect changes in *mood*, *sentiment* or *emotional state* of the crowd (Baig et al., 2014; Cai, 2013). This can also help improve operational safety, while providing objective feedback about attendees' level of service/satisfaction (while it should be ensured that adequate measures are taken for this practice to be protective of individual privacy). There is no single universally accepted method for measuring the sentiment. However, there are several approaches that can provide insights into the emotional state of the crowd. One approach is to monitor social media and other online platforms to track the sentiment of attendees. This involves analysing the language and tone used in social media posts and other online communications to determine the overall mood of the crowd (Wakamiya et al., 2015). An alternative approach is through visual analysis and surveillance input (Baig et al., 2014; Sánchez et al., 2020; Zhang et al., 2021). In addition, event organisers can also gather feedback from attendees through surveys, questionnaires, or interviews. These methods can provide valuable insights into the emotional state of the crowd and enable organizers to

[14] The core problem about near misses is that virtually no-one publishes near-miss incidents out of fear for a negative backlash or legal action. It will be crucial to set-up an anonymous reporting system on a freely accessible platform for such information to be shared, interpreted, and learned from. At present, details about non-catastrophic crowd safety failures are often near impossible to obtain.

identify areas for improvement in future events.

15.4. The role of security personnel and their preparedness in crowd safety

The interaction of security personnel in crowded spaces can have a significant impact on crowd behaviour. The presence of security personnel can provide a sense of reassurance and safety to attendees, while also deterring potential security threats. However, if security personnel are perceived as overly aggressive or confrontational, this can exacerbate tensions and escalate the risk of incidents. To improve the interaction of security personnel in crowded spaces, several strategies can be employed. By employing these strategies, event organizers can ensure that security personnel interact with crowds in a professional, non-confrontational manner, minimizing tensions and promoting a safe and welcoming environment for all attendees (Ammon Jr and Fried, 1999; Hope et al., 2023; Ludvigsen, 2023).

- *Regular & comprehensive training*: Security personnel should receive comprehensive training in conflict resolution, de-escalation techniques, and effective communication skills. This training should also emphasize the importance of maintaining a calm and professional demeanour, even in high-pressure situations (Terrill and Zimmerman, 2022).
- *Clear guidelines*: Event organisers should establish clear guidelines for the behaviour of security personnel, including protocols for engaging with attendees and responding to potential incidents. These guidelines should emphasise the importance of non-violent, non-confrontational approaches wherever possible (Earl et al., 2004b).
- *Visibility and positive interactions*: Security personnel should be highly visible to attendees, which can help to deter potential security threats and provide a sense of reassurance to attendees. However, this visibility should be achieved through non-intrusive means, such as the use of high-visibility vests or branded clothing, rather than through aggressive posturing or confrontational behaviour (Hayes-Jonkers et al., 2011, 2012).
- *Role description & title*: The word 'security' emblazed across clothing can cause a negative reaction in parts of the community and even in the person wearing the uniform. Changing the name and description to 'marshal' or similar titles may reduce that risk.
- *Evaluation & feedback*: Regular evaluation and review of security protocols and personnel performance can help to identify areas for improvement and ensure that best practices are being followed. This evaluation should include feedback from attendees and staff to identify any areas where improvements can be made (Campbell III, 2023; Pointing et al., 2012).
- *Effective communication & collaboration*: Security personnel should communicate clearly and effectively with attendees, providing clear instructions and directions, and responding promptly to requests for assistance or information. Security personnel should also work collaboratively with other event staff, including medical personnel, and volunteers.

15.5. Specific safety needs of vulnerable individuals

Vulnerable individuals and particularly people with physical disabilities and limited mobility face a range of unique challenges when it comes to crowd safety (Adams and Ward, 2020; Feliciani et al., 2020; Karthika et al., 2022; Rismanian and Zarghami, 2022; Terashima and Clark, 2021). Many venues and events may not be designed with accessibility in mind, which can make it difficult for individuals with disabilities to enter and exit the premises safely. This can also make it challenging to evacuate the area quickly in the event of an emergency. Also, individuals with disabilities may not be able to see over crowds or barriers, which can make it difficult to navigate through crowded areas or to identify potential hazards. Furthermore, individuals with disabilities may require assistance to move through crowded areas or to evacuate in the event of an emergency (Fu et al., 2022; Hashemi, 2018; Hostetter and Naser, 2022).[15] This can be challenging if there are not enough trained staff or volunteers available to provide assistance (Geoerg et al., 2022; Tong and Bode, 2023).

Ensuring crowd safety for individuals with disabilities requires careful planning and consideration of their unique needs and challenges. This may involve providing accessible facilities and accommodations, training staff and volunteers to assist individuals with disabilities, and developing clear communication and evacuation plans that take into account the needs of all attendees. If possible, people having physical disabilities should be directly consulted as it is difficult for able-bodied people to understand their challenges. Engaging people having any sort of handicap would be clearly difficult but at least the most commonly represented categories should be consulted (e.g., elderly, people on wheelchairs, individuals with hearing or visual impairments, etc.).

On the research front, there is a clear knowledge gap about safety issues of crowds that have mixed-ability make-up, although the body of research on this issue is slowly growing. Further research into the interactions of people with limited mobility with the rest of the crowd and vice versa could assist in developing better informed guidelines and practices (Geoerg et al., 2018; Geoerg et al., 2022).[16]

15.6. Value of statistical life (VSL) in crowd safety

The notion of value of statistical life (VSL) is an important concept in crowd safety that refers to the monetary value that society places on preventing a single uncertain fatality. VSL does not measure the intrinsic value of human life, but estimates how much people are willing to pay to reduce their risk of mortality, and it is often used as a standard for evaluating the benefits of safety interventions (Viscusi, 2012; Viscusi and Aldy, 2003). In other words, it represents the amount of money that a society would be willing to invest to prevent one uncertain death. By taking into account the economic and social costs of fatalities and injuries, decision-makers can work towards making environments safer and more secure on the whole, using reasonable measures.

This value is used to evaluate the cost-effectiveness of policies and interventions aimed at reducing the risk of injury or death in crowded places. In the context of crowd safety, the VSL can be used to estimate the value of safety measures and to determine whether the costs of implementing those measures are justified by the potential benefits. As an illustrative example, if a crowd management system costs $1 million to implement but is estimated to save one life, and the VSL is $5 million, then the benefits of the system are greater than its costs, and it should be implemented. But the challenge would be how to quantify the safety benefits in monetary terms. The importance of the VSL lies in its ability to help decision-makers prioritise and allocate resources in the most efficient way possible. By comparing the expected costs and benefits of different safety measures, policymakers can make informed decisions that maximise the overall welfare of society. Cost-benefit approaches should also strive to take into account the psychological and social fallout of potential tragedies.

[15] With respect to matters of crowd evacuation, there needs to be a clear distinction between the crowds where individuals with disability are in the minority compared to the situations where the crowd is predominantly composed of individuals with limited mobility, e.g., a hospital or aged-care evacuation. The dynamics of these two crowds may be vastly different.

[16] An example of an Australian standard is AS1428.1 2021 – Design for access and mobility general requirements for access sets out clear standards for new building works. As all temporary events structures can be deemed 'new work' the Standard sets out clear expectations in terms of accessibility for people with disabilities. The Commonwealth Disability Discrimination Act also sets out conditions to eliminate discrimination against persons on the grounds of disability in work, accommodation, education, access to premises, clubs and sport; & provision of goods, facilities, services and land.

There is currently a clear gap in the existing knowledge about VSL in crowd safety. While an abundance of research has been undertaken with respect to VSL in other life-saving contexts such as disease prevention/cure (Telser and Zweifel, 2007) and road safety (de Blaeij et al., 2003), there is no study to this date that has estimated this number in the context of crowd safety.

The applications of knowing the VSL in crowd safety are numerous. For example, it can be used to determine the appropriate level of investment in crowd management infrastructure, such as barriers, signage, emergency services, hiring experienced crowd safety professionals/experts for events or running safety culture campaigns. It can also inform the development of regulations and guidelines for event organisers and venue operators. How the estimate varies from country to country can tell much about the extent to which different societies are willing to invest in improving crowd safety (Miller, 2000).

Estimating the VSL is a relatively complex task. One approach is to conduct surveys that ask individuals about their willingness to pay for risk reduction measures, such as improved crowd control, implementation of technologies, and enhanced emergency response. The alternative approach is to present them with hypothetical choice scenarios that present implementation of various crowd safety measures along with their attributes (e.g., cost, degree of effectiveness) and infer their monetary valuation from the choices that they make (Haghani et al., 2021a, b; Hensher et al., 2009, 2011).

15.7. The need for collaborations between academics, practitioners and stakeholders

Academics and practitioners of crowd safety can work together in several ways to improve safety capabilities and reduce risks to events and crowds. Moreover, the engagement of academics and practitioners with other crowd safety stakeholders can help create a more collaborative, informed, and effective approach to crowd science and practice. Some potential areas of collaboration include:

- *Collaborate on research*: Academics can conduct research to develop new theories and approaches to crowd safety, while practitioners can provide real-world experience and data to inform the research. Collaboration between the two groups can lead to better understanding of the factors that contribute to crowd safety and help identify effective interventions and best practices.
- *Share knowledge and expertise*: Practitioners can share their knowledge and expertise with academics, providing insight into the practical challenges of crowd safety management.
- *Develop and deliver training courses*: Academics can work with practitioners to develop and deliver training programs on crowd safety.
- *Conduct joint exercises and simulations*: Academics and practitioners can work together, beyond the existing levels, to conduct joint exercises and simulated experiments to test and improve crowd safety procedures and further the empirical knowledge on crowd safety. This can help better align the work of academics with the needs of crowd safety professionals.
- *Test lab-developed solutions and technologies in a real scenario*: Technologies developed in the frame of academic research are typically tested in controlled laboratory conditions which are different from real crowd events. Having the possibility to test those solutions in a real context can help academics understand challenges faced in reality and practitioners can learn about state-of-the-art technologies before they become commercially available.
- *Engagement and outreach with stakeholders*: Academics and practitioners can work together to engage with stakeholders, including event organisers, local authorities, and the public, to raise awareness of crowd safety issues and promote best practices. This can involve developing educational materials, conducting public outreach, and providing technical assistance to event organisers and authorities, and involving stakeholders in co-designed research.

Engagement of academics and practitioners with crowd safety stakeholders can be helpful in improving crowd science and practice in several ways: including (a) developing a better understanding of the needs and challenges faced by crowd safety stakeholders, (b) bridging the gap between theory and practice, (c) improving the dissemination and adoption of research (by involving stakeholders in the research process, they are more likely to be invested in the findings and more likely to implement the recommended solutions), and (d) encouraging innovation.

16. The Swiss Cheese model of crowd safety

In the previous sections, we discussed a range of dimensions, tools, and aspects of crowd safety. But the question remains, what is the best way to ensure crowd safety? Is there a gold standard or panacea solution to the crowd safety problem? We believe there is no panacea solution. There is no single method of practice that can ensure crowd safety per se. However, drawing parallels to a well-known concept and a tangible metaphor in risk management, known as The Swiss Cheese Model (Larouzee and Le Coze, 2020; Reason, 1990, 2000; Reason et al., 2006), here we propose that a system of multiple layers of safety protection could be the key in crowd safety practice. We refer to this model as The Swiss Cheese Model of Crowd Safety. The components of this model have previously been unpacked in earlier sections. Here, we explain how they can fall under the umbrella of a unified model.

The Swiss Cheese Model is a concept used in risk management and safety engineering that helps explain how multiple layers of defence can help prevent accidents and errors. The Swiss Cheese Model is named after Swiss cheese, which has a distinctive appearance due to the holes or gaps in its structure. The model visualises these holes as potential weaknesses in a system, and the layers of cheese as the various defences that are put in place to prevent a failure. Within this metaphorical representation, system failure and catastrophes only occur if there is an alignment of holes across all layers. The model is based on the premise that individual safety protection measures are never perfect and are subject to flaws, and that each layer of protection has the potential to fail. But by having multiple layers in place, the likelihood of a critical failure occurring is significantly reduced. In other words, a multi-layer safety protection mechanism would ensure that the system does not fail unless all individual layers fail, an unlikelier event compared to the failure of a single layer.

The Swiss Cheese Model is often used in industries where safety is critical, such as aviation, healthcare, and nuclear power. In that sense, there is also a perfect fit here to the notion of crowd safety. Each individual aspect of crowd safety protection that was discussed in earlier sections— including (a) policy and legislation, (b) pre-planning and risk assessment (c) operation and control (d) community preparedness and (e) incident response and impact mitigation—could be considered as a layer of the Swiss Cheese Model of Crowd Safety (Fig. 1). Policy and legislation ensure the existence of pre-planning and operation control through mandates. Our planning tools as well as the data and information we do the pre-planning based on are all imperfect and they might not be fully accurate. The placement of operational control measures, however, can compensate for errors in planning should they occur and save the system from failure. But operational control itself is also subject to limitations, and when failure at that level also aligns with inadequate planning, one may hope that the community and people are equipped with the knowledge of safe behaviour and what to do to avert a disaster and/or mitigate it. And in an unfortunate case, where all previous layers fail to protect the system, efficient contingency planning and emergency response could be the last layer of defence that can minimise the adverse impacts of previous failures.

17. Summary and concluding remarks

In light of the content that was presented previously, we put forward

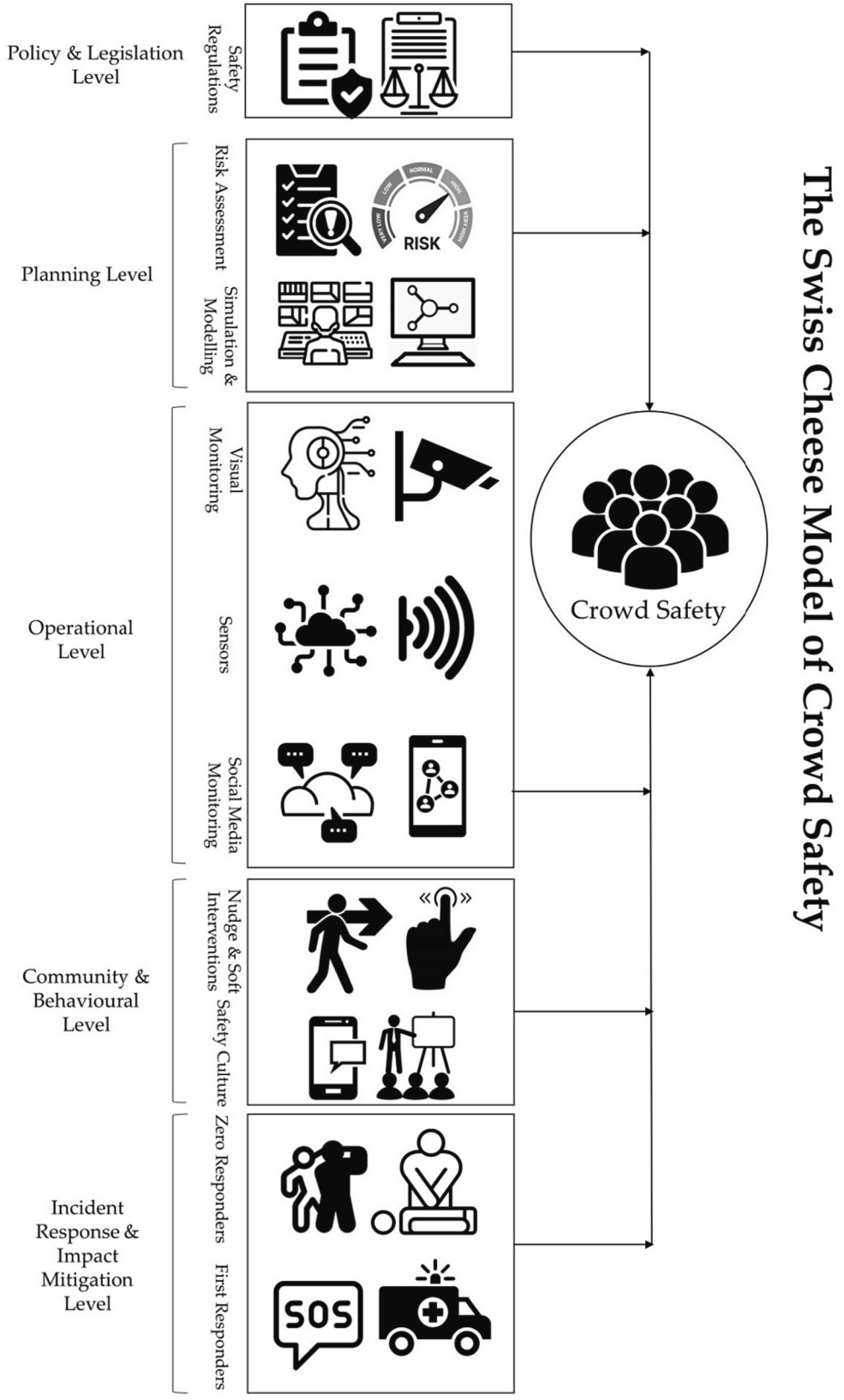

Fig. 1. A multi-layered safety protection paradigm. The Swiss Cheese Model of crowd safety.

two major recommendations that we believe have potential to tangibly enhance crowd safety practice:

(i) *The development, adoption and deployment of a holistic multi-layer crowd safety paradigm that encompasses (a) policy and legislation level, (b) pre-planning and risk assessment level, (c) operational and control level, (d) community preparedness and behavioural level, and*

(e) incident response and impact mitigation level. Such safety system will have parallels to the well-known Swiss Cheese Model of accidents will make maximal use of the potential of technology—including AI, computer vision, computer simulation, sensors and social media data—at both planning and operational levels. Each layer of protection can have its own weaknesses or potential for failure. However, by having multiple layers of protection in place, the chances of a hazard passing through all layers and causing harm are significantly reduced. In other words, the multi-layer nature will ensure that failure at one level does not translate to a failure of the system and thereby a disaster. For instance, it is possible that poor or inadequate planning can be compensated for by advanced operational control. Similarly, preparedness at the community level can help avert disasters in

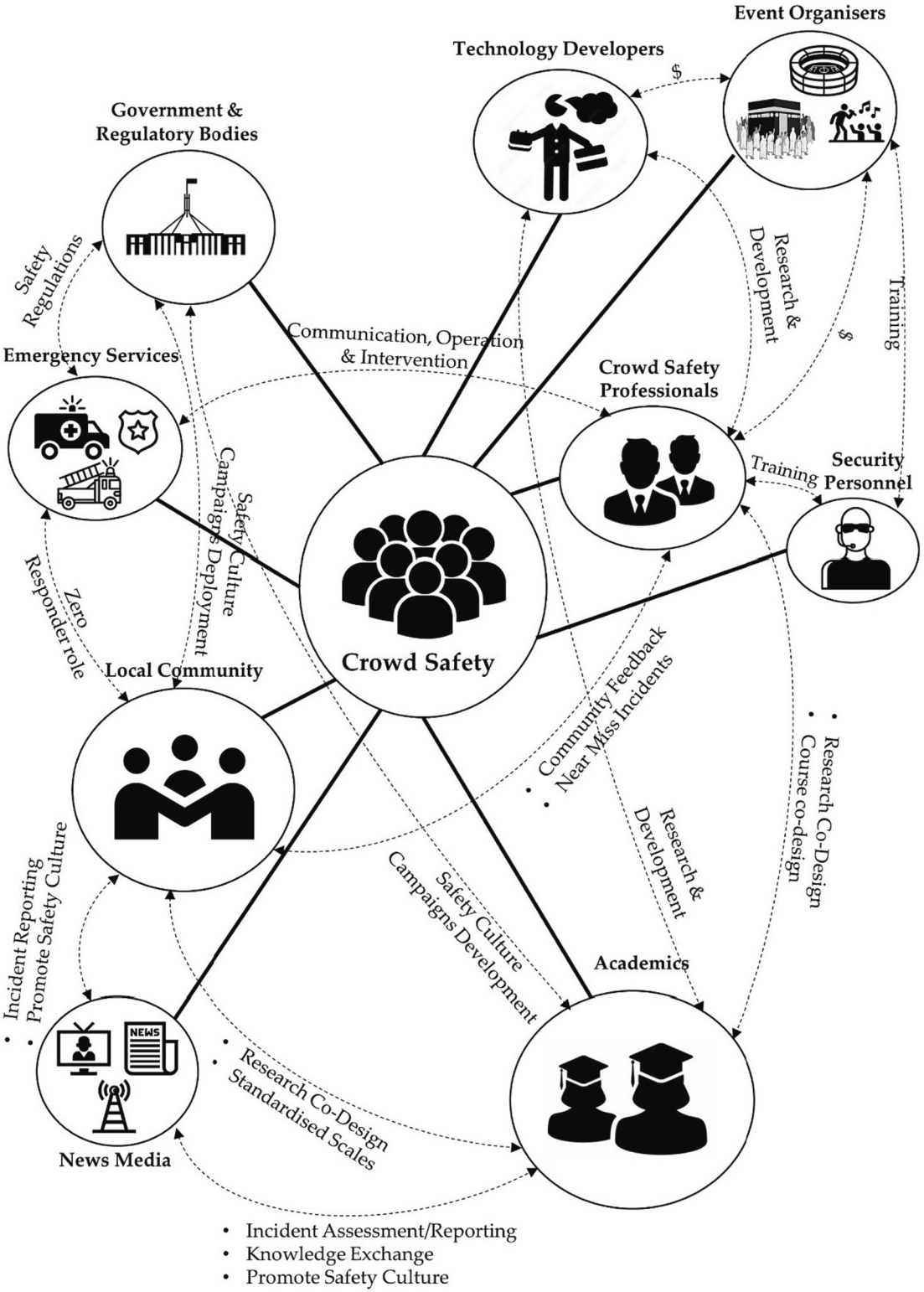

Fig. 2. Stakeholders of crowd safety and their potential ways of collaboration and interactions.

cases when both planning and operational control levels have failed.

(ii) *Improved communication and interaction between various stakeholders of crowd safety.* The multi-layer system that was proposed cannot be successfully implemented without close collaboration of all major stakeholders. Fig. 2 illustrates some of the most significant forms of interactions where these collaborations can potentially contribute to crowd safety. Development of crowd safety culture and community preparedness, for example, is a task that cannot be achieved by a single entity. It requires collaborations between academics, community, government, crowd safety professionals and the media. Co-designed research that involves crowd safety professionals, academics and the community is also another major missing element, creating a divide between the efforts of academics and the needs of the society and practitioners. Significant progress can be expected in both science and practice by expanding, intensifying and fortifying the existing interactions and collaborations between the crowd safety stakeholders.

(iii) We hope that the current work contributes to bridging the above-mentioned divide and to enhancing crowd safety research and practice. Our conclusion is that crowd safety is an emerging and evolving science, and so is its practice that has been considerably improving over the years, particularly by embracing the role of technology in crowd safety. There is, however, no panacea solution to the crowd safety problem, and that is implied by our proposed conceptual model too. We suggest that safety targets are only achievable through a multitude of layers of safety assurance. We recommend that this multi-layer safety protection model becomes the norm of the practice and that researchers, practitioners, government agencies and other stakeholders work closely on these individual layers to make them more effective and more robust to errors. This will not be achieved unless there is a greater recognition for stakeholder collaboration and communication in the crowd safety domain, beyond its existing levels. Part of that would be greater financial investment in crowd safety, both in public and private sectors and the recognition that this is a major and important aspect of public safety that is worth investing in. Similar to *Vision Zero*, as a multinational initiative to reduce road accident deaths to zero, a similar global strategy should be adopted for crowd safety. That would require monetary investment and recognition at the level of local governments and ultimately at a global level.

CRediT authorship contribution statement

Milad Haghani: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Matt Coughlan:** Writing – review & editing, Investigation, Conceptualization. **Ben Crabb:** Writing – review & editing, Investigation, Conceptualization. **Anton Dierickx:** Writing – review & editing, Investigation, Conceptualization. **Claudio Feliciani:** . **Roderick van Gelder:** Writing – review & editing, Investigation, Conceptualization. **Paul Geoerg:** Writing – review & editing, Investigation, Conceptualization. **Nazli Hocaoglu:** Writing – review & editing, Investigation, Conceptualization. **Steve Laws:** Writing – review & editing, Investigation, Conceptualization. **Ruggiero Lovreglio:** Writing – review & editing, Investigation, Conceptualization. **Zoe Miles:** Writing – review & editing, Investigation, Conceptualization. **Alexandre Nicolas:** . **William J. O'Toole:** Writing – review & editing, Investigation, Conceptualization. **Syan Schaap:** . **Travis Semmens:** Writing – review & editing, Investigation, Conceptualization. **Zahra Shahhoseini:** Writing – review & editing, Investigation, Conceptualization. **Ramon Spaaij:** . **Andrew Tatrai:** Writing – review & editing, Investigation, Conceptualization. **John Webster:** Writing – review & editing, Investigation, Conceptualization. **Alan Wilson:** .

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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