



Risk Analysis of Stampede in New Delhi Railway Station and Social Policy

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Abstract India has experienced many fatal stampedes during major religious gatherings, with railway stations often becoming critical points of vulnerability due to overcrowding, delays, and insufficient crowd control infrastructure. Another stampede occurred on June 4, 2025, outside a cricket stadium in Karnataka during celebrations of the Indian team's victory in the Indian Premier League (IPL). Despite the recurring nature of these tragedies, risk modelling frameworks specifically designed for high-density transit environments are limited. This study addresses this gap by conducting a comprehensive risk analysis of stampede events at New Delhi Railway Station, a key transit hub during the MahaKumbh and similar mass gatherings. The research employs a hybrid methodology combining Catastrophe Theory and Bayesian Networks within a Bow-Tie framework, enabling dynamic modelling of nonlinear crowd behaviour and probabilistic inference under uncertainty. The model includes 92 interconnected variables covering behavioural, infrastructural, operational, and emergency response factors. Due to the lack of detailed empirical data, the Delphi method was used to derive conditional probabilities based on expert judgment, ensuring relevance and methodological robustness. The findings indicate a base-case likelihood of 62.9% for stampede occurrence, with panic behaviour, train delays, communication failures, and group agitation identified as key risk factors. Public safety policies should incorporate these insights to improve urban safety and emergency response strategies, facilitating proactive decision-making, real-time hazard monitoring, and system-level interventions to prevent crowd disasters and enhance public safety.

Keywords: disaster, stampede, risk analysis, mitigation of risk, catastrophe theory, sensitivity analysis, social policy

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1. INTRODUCTION

Mass gatherings are deeply ingrained in India's cultural and religious life, drawing millions of participants to events such as the Kumbh Mela, temple festivals, and other spiritual gatherings. These occasions, while spiritually significant, present serious logistical and safety challenges, particularly in terms of crowd control and disaster preparedness. Among the most severe and frequent hazards at such events are stampedes, which have repeatedly resulted in large-scale loss of life and injury. Between 2001 and 2022, over 3,000 people lost their lives in stampede-related incidents across India, with the majority of these occurring during religious events (*Over 3000 Lives Lost in Stampedes between 2001-2022*, 2022). Illiyas et al. (2013) further confirm this trend, showing that nearly 80% of stampedes between 1954 and 2012 happened at religious sites. These statistics underscore a persistent and critical issue that threatens the safety of millions each year. Stampedes often happen in India and worldwide when large crowds gather in one place. Approximately 11 people have been killed and many more injured in a stampede outside a cricket stadium in the Southern Indian state of Karnataka. People were gathered to celebrate the home team's victory in the Indian Premier League (IPL) T-20 cricket tournament. The stadium has a capacity of 35,000 people, whereas 200,000 – 300,000 people came, and a stampede resulted due to overcrowding at the stadium.

In January 2025, around 6 people died and over 40 were injured due to a lack of adequate arrangements to manage the crowd at the Tirumala temple.

The risk is especially acute at transit points like railway stations, which become heavily congested during mass events. For instance, a stampede at the Allahabad railway station during the 2013 Kumbh Mela led to 36 deaths (Bhardwaj, 2025). More recently, a similar tragedy unfolded during the 2025 Maha Kumbh Mela in Prayagraj, resulting in at least 30 fatalities (Singh & Saaliq, 2025). In February 2025, another stampede at New Delhi railway station claimed 18 lives, including children (Bhardwaj, 2025). These incidents highlight how railway stations—designed for steady commuter flow—become critical bottlenecks under sudden mass influxes, making them uniquely susceptible to crowd disasters. Railway and metro platforms, originally intended to handle daily traffic, are increasingly being overwhelmed during such gatherings. (Zhou et al., 2023) demonstrated that as metro systems become central to urban transportation, risks associated with resident variability and platform overcrowding grow substantially. Their work proposed a passenger travel model and a crowd risk analysis method to better manage these dynamic environments and minimize stampede risks.

The underlying causes of stampedes are multifactorial. Common factors include high crowd density, insufficient infrastructure (e.g., narrow exits or blocked passages), abrupt crowd surges, and a lack of real-time monitoring systems (Weng et al., 2023). The review paper of Alaska et al. (2017) on crowd dynamics during the Hajj pilgrimage, emphasized the importance of crowd simulation models and engineering controls for pre-emptive planning and management. Without such mechanisms, even a minor disturbance can quickly escalate into a catastrophic stampede. A growing body of research has focused on optimizing transportation management during large events. Yuan et al. (2020) proposed a genetic algorithm-based model for

optimizing train delays and passenger transfer processes in high-demand urban rail settings. Similarly, Chen et al. (2024) explored the effectiveness of Bus Bridging Services (BBS) in mitigating passenger congestion during subway disruptions. Their findings from the Chengdu subway system in China indicated that extended BBS and passenger guidance systems can significantly enhance emergency response and reduce congestion.

In the Indian context, Illiyas et al. (2013) advocate for a disaster risk reduction framework tailored to mass gatherings, focusing on early detection and timely intervention. Complementing this, Hashim and Amutha (2022) used a Candidate Classification Technique (CCT) to effectively monitor and classify crowd behavior during Hajj, facilitating faster and more accurate responses. Despite these advancements, there is a noticeable gap in the literature and practice regarding the specific risks posed at railway stations during religious events in India. Most existing models and policies are tailored to fixed venues like stadiums or open fields and fail to address the unique structural and operational characteristics of railway infrastructure. Similar to how Ramasamy et al. (2011) assessed the impact of low-cost vehicle modifications in reducing fatalities from landmine explosions, this study examines how targeted structural and operational interventions can mitigate stampede risks in railway environments. Composite performance indices, like those used by Coll et al. (2013) to identify and prioritize traffic safety hotspots, and provide a methodological foundation for risk-based ranking of vulnerable transit locations during mass gatherings.

To address this gap, the present study focuses on risk analysis for stampede events in crowded railway stations, especially during large-scale religious gatherings such as the Maha Kumbh. Using a hybrid methodological framework that integrates Catastrophe Theory (CT) and Bayesian Networks (BN), based on the work of Hu et al. (2022) this research aims to identify critical hazards, simulate dynamic risk evolutions, and support evidence-based mitigation strategies.

The key research questions guiding this study are as follows:

1. What are the primary factors contributing to stampede incidents at railway stations during mass gatherings?
2. How can existing crowd management and risk modeling techniques be adapted to address the unique challenges posed by railway stations?
3. What proactive, scalable measures can be implemented to prevent stampede events in these environments?

By answering these questions, this research seeks to contribute toward a more resilient infrastructure and management strategy for large-scale public events, with a specific focus on high-risk transit environments.

The remainder of this paper is structured as follows. Section 2 reviews relevant literature on stampede incidents, crowd risk modeling, and transportation-based mass gathering management. Section 3 explains the methodological approach, detailing the integration of CT, BN, and the Delphi Method (DM). Section 4 describes the construction of the risk analysis

model tailored to crowded railway stations. Section 5 presents and discusses the results from scenario simulations and sensitivity analyses. Finally, Section 6 concludes the study by summarizing the findings, outlining practical implications, and suggesting future research directions.

2. LITERATURE REVIEW

Understanding and mitigating stampede risks in large-scale public venues has gained considerable scholarly attention, especially in contexts involving religious mass gatherings and crowded transit environments. Multiple methodological frameworks have been proposed to assess, predict, and manage crowd-related hazards. This section reviews key contributions that inform the current study, focusing on integrative risk modeling, flow control optimization, and socio-behavioral dimensions of crowd management. Hu, Zhao, and Bai (2022) present a significant contribution to the field by proposing an integrated framework for stampede risk analysis in large-scale sporting venues, which is also applicable to similar high-density environments such as railway stations. The authors underscore that traditional static risk assessment tools—such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and the Analytic Hierarchy Process—are insufficient for modeling dynamic, time-sensitive events like stampedes. These methods are limited in their capacity to capture the temporal evolution and nonlinear nature of crowd behavior under stress. To overcome these limitations, Hu et al. (2022) advocate for the integration of BNs and CT. BNs are probabilistic graphical models that represent conditional dependencies among random variables using directed acyclic graphs. They are particularly well-suited for complex, uncertain systems where empirical data may be sparse or incomplete. In the context of stampede prediction, BNs enable dynamic inference and allow for scenario-based analysis by updating posterior probabilities in response to observed conditions.

Complementing the BN, CT is used to model the discontinuous state transitions often observed in crowd systems, such as the sudden shift from ordered movement to chaotic panic. Catastrophe systems are characterized by properties such as multistability, hysteresis, sharp transitions, and divergency—features that align well with the emergent nature of stampedes. Hu et al. utilize potential functions to represent system energy states and model interactions between control variables (e.g., crowd density, information flow) and state variables (e.g., panic level). The authors demonstrate that integrating these theories within a Bow-Tie (BT) structure—used to visually map causal pathways and mitigation strategies—provides a robust and adaptable tool for both hazard identification and consequence prediction. Key contributing factors to stampede risk identified in their study include human error, site infrastructure failure, environmental impacts, and management deficiencies. Scenario-based simulations and sensitivity analyses are employed to diagnose critical failure points and evaluate potential interventions. In a related line of research, Liang et al. (2023) address crowd control from an operational optimization perspective. Their study focuses on flow control mechanisms in metro systems and proposes a real-time passenger admission model designed to maximize either

passenger throughput or revenue efficiency. The authors frame the problem as a stochastic dynamic programming task and apply advanced mathematical tools, including Blackwell's approachability theorem and Fenchel duality, to describe the service-level trade-offs among various origin-destination pairs.

The study compares three control policies: First-Come-First-Served (FCFS), Revenue Maximization Policy (RMP), and a Fairness-Oriented Policy (FOP). FCFS aggressively fills available train capacity without considering downstream demand, which can exacerbate congestion. RMP focuses purely on maximizing load, potentially neglecting equitable access. In contrast, FOP ensures a minimum service level across OD pairs while still optimizing total load. This work is particularly relevant for high-volume transit hubs during mass gatherings, where balancing efficiency and equity is critical to avoiding overcrowding and panic-inducing scenarios. The findings highlight the need for adaptive flow control algorithms that account for real-time passenger distribution, platform congestion, and boarding behavior under uncertainty. The socio-psychological dimensions of crowd behavior are further explored by Al-Ahmadi et al. (2021), who studied visitor dynamics at the Prophet Muhammad's (PBUH) tomb during Ziara in Madinah. This location represents one of the most densely packed pilgrimage sites in the world, with visitor volumes frequently exceeding 9,200 persons per hour. The authors developed a regression-based model to analyze movement thresholds and identify risk thresholds, noting that waiting times exceeding 42 seconds in front of the Moajha can precipitate destabilization in crowd flow.

The study emphasizes the importance of capacity analysis—a metric of the volume of pedestrian traffic that can safely traverse a route. Indicators such as travel time, walking speed, and Level of Service are used to assess infrastructure performance. The authors also stress the significance of socio-environmental variables such as crowd size, inter-agent interactions, and spatial layout. Importantly, they note that socio-psychological factors—including language barriers, cultural norms, and individual behavioral traits—profoundly influence collective movement patterns and the potential for crowd panic. This research contributes vital insights into the behavioral and psychological underpinnings of crowd dynamics, reinforcing the need for culturally informed and demographically sensitive crowd management strategies. The output of the study provides actionable guidance for decision-makers in designing congestion mitigation protocols, optimizing waiting times, and enhancing spatial planning at high-risk religious sites.

Collectively, these studies offer complementary perspectives on the multifaceted nature of stampede risks. Hu et al. (2022) provide a robust modeling framework for probabilistic and nonlinear risk analysis; Liang et al. (2023) offer optimization-based tools for real-time flow control; and Al-Ahmadi et al. (2021) bring attention to socio-psychological influences in extreme density environments. These frameworks collectively inform the methodological foundation of the present study, which aims to develop an integrated, data-informed, and scalable model for risk assessment in crowded railway stations during mass gatherings.

3. METHODOLOGY

A comprehensive and integrated risk analysis framework is proposed to investigate stampede incidents occurring in crowded railway stations. This methodology synthesizes the BT method, BNs, CT, and the DM to construct a dynamic and probabilistic risk model. To contextualize the risk environment, Figure 1 presents a schematic layout of New Delhi Railway Station. The layout highlights key zones of crowd congregation, such as platforms, staircases, foot overbridges, entry gates, and waiting areas, which are critical to understanding spatial risk distribution and identifying potential stampede triggers. The layout highlights key zones of crowd congregation, such as platforms, staircases, foot overbridges, entry gates, and waiting areas, which are critical to understanding spatial risk distribution and identifying potential stampede triggers. The station features two major access points—Paharganj and Ajmeri Gate—each channeling large volumes of foot traffic through designated drop-off zones, bus bays, and metro connections. With 16 platforms interconnected by three-foot overbridges (FOBs), the layout reveals high-risk congestion points at staircases, escalators, and bridge exits, especially during peak travel hours. The presence of waiting rooms, lounges, and service counters along platform sides adds to localized crowding and potential evacuation bottlenecks. Additionally, the station's multimodal integration with buses, metros, and taxis increases external crowd pressure at entry points, underscoring the need for coordinated flow management and real-time crowd monitoring solutions.

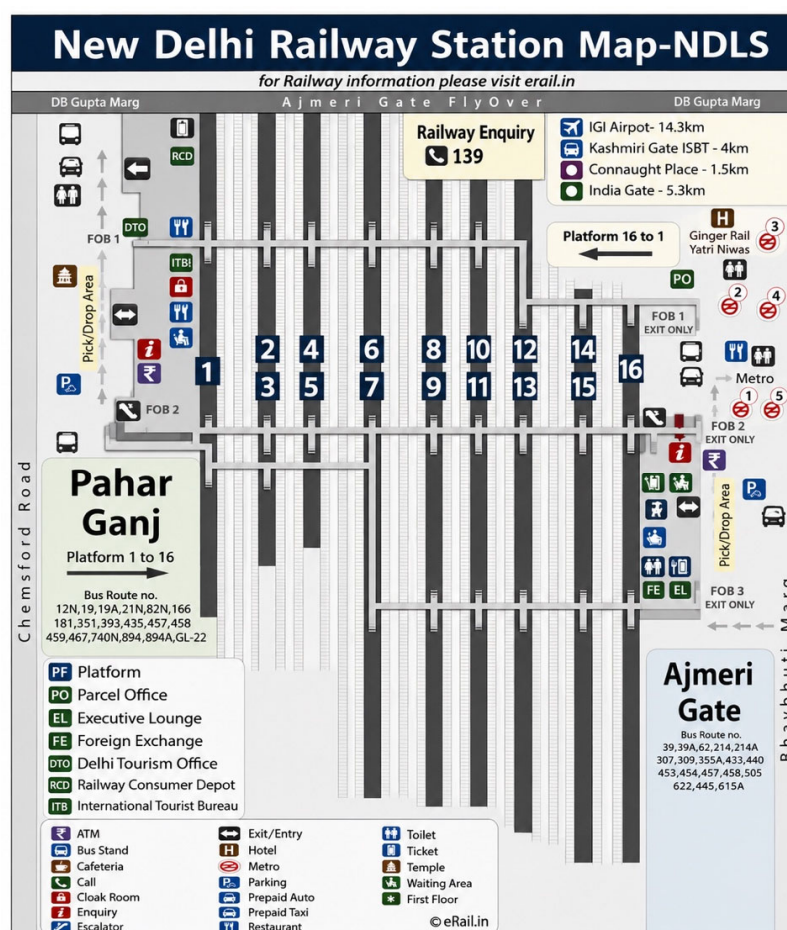


Figure 1. Schematic layout of New Delhi Railway Station

3.1 Bow-Tie Method

The BT method, originally developed in the 1970s, integrates FTA and ETA to systematically model the causes and consequences of accidents. It has been widely used in process safety, infrastructure risk assessment, and disaster management due to its intuitive graphical representation and logical structure.

In this study, the BT method is adapted to the context of railway stations, where stampede incidents can be triggered by a combination of human error, infrastructure failure, environmental conditions, and management deficiencies. The top event—stampede occurrence—is decomposed into four primary causal branches. Sub-fault trees are constructed for each domain based on empirical observations, incident reports, and expert elicitation. The event tree defines safety barriers (e.g., crowd control, emergency communication) and potential outcomes (e.g., casualties, operational disruption, economic losses), supporting a full-chain risk analysis.

3.2 Bayesian Network

BNs are probabilistic graphical models comprising nodes and directed arcs that represent random variables and their conditional dependencies. They are especially effective in complex risk environments, where causal relationships are uncertain, and data may be sparse or incomplete (Akhavan et al., 2018). Using the BT structure, a BN is constructed to model stampede risks in railway stations. Root nodes represent primary hazards (e.g., overcrowded platforms, delayed train announcements), intermediate nodes describe the propagation of risk factors (e.g., panic movement, crowd turbulence), and the pivot node represents the top event (stampede). Consequence nodes reflect possible outcomes. Safety barriers are modeled as control variables influencing the likelihood of escalation.

A total of 92 nodes is included in the BN, including 52 root nodes, 36 intermediate nodes, one pivot node, and four consequence nodes. Conditional Probability Tables (CPTs) are specified using a combination of historical data and expert elicitation. Bayesian inference allows updating of posterior probabilities based on observed evidence, supporting both scenario prediction and root cause diagnosis.

The model is implemented using **AgenaRisk software** (Agena Ltd., Cambridge, UK), which facilitates probabilistic modeling and supports dynamic inference, sensitivity analysis, and scenario-based simulations.

3.3 Catastrophe Theory

CT, introduced by Thom (1972), provides a mathematical framework for modeling discontinuous transitions in dynamic systems. It has been applied across diverse domains, including crowd behavior, safety systems, and socio-technical risk modeling.

In railway environments, crowd dynamics often exhibit abrupt shifts from stable to chaotic states due to nonlinear interactions between control variables such as crowd density and environmental stimuli. The catastrophe model is defined using a potential function:

$$V = f(U, X) \quad (1)$$

where $U = \{u_1, u_2, \dots, u_m\}$ denotes control variables and $X = \{x_1, x_2, \dots, x_n\}$ denotes state variables. The system's equilibrium conditions are given by:

$$\frac{\partial V}{\partial x} = 0 \quad \text{and} \quad \frac{\partial^2 V}{\partial x^2} = 0 \quad (2)$$

Depending on the number of variables involved, fold, cusp, swallowtail, or butterfly models may be used. In this study, the cusp model is commonly applied where two control variables—such as platform density and information clarity—jointly influence the state variable “panic behavior.” Normalization formulas are used to quantify the relative influence:

$$x_1 = \sqrt{u_1}, \quad x_2 = \sqrt[3]{u_2} \quad (3)$$

The normalized values are used to determine membership function values, which are then translated into conditional probabilities for the BN. This integration enhances the network's ability to capture nonlinear system behavior and abrupt transitions.

3.4 Delphi Method

The DM is a structured group communication technique designed to achieve consensus among experts through multiple rounds of questionnaires with controlled feedback. It has been widely used in risk analysis, safety assessment, and policy forecasting under uncertainty.

In this study, the DM is used to construct the CPTs for the BN where empirical data are insufficient. A panel of five experts—comprising railway operations managers, safety engineers, and academic researchers—participated in three rounds of elicitation. The experts evaluated the influence of root and intermediate nodes on their child nodes using numerical scoring.

While the standard DM recommends 8–10 or more experts, this study employed five due to the interdisciplinary nature of the panel—comprising railway operations managers, safety engineers, and academic researchers—and resource constraints. This is acknowledged as a methodological limitation that may introduce subjectivity, which future studies should address with larger panels.

Cronbach's alpha was used to test the internal consistency of responses, with thresholds above 0.9 indicating strong agreement. The Cronbach's alpha coefficient achieved across all elicitation rounds was $\alpha = 0.923$, meeting the threshold of $\alpha > 0.9$ required to confirm strong inter-rater agreement among the expert panel. The resulting influence values were normalized using Eq.3, and the conditional probabilities were derived as:

$$p_{jt} = \frac{m_{jt}}{\sum m_{jt}} \quad (4)$$

where m_{jt} is the membership function value for state j under combination t . This hybrid approach reduces subjectivity and increases the fidelity of the BN model in reflecting real-world dynamics.

To illustrate the CPT construction process, consider the intermediate node 'Panic Behavior' (I3), which has two parent nodes: 'Aggressive Movement' (R6: Frequent/Occasional) and 'Train Delay' (R47: Short/Moderate/Long). The cusp catastrophe model is applied with u_1 = expert score for R6 and u_2 = expert score for R47, normalized as $x_1 = u_1$ and $x_2 = \sqrt[3]{u_2}$. The resulting membership function values are summed and used to derive final conditional probabilities as $p(j|t) = m(j,t) / \sum m(j,t)$. For the combination (R6=Frequent, R47=Long), expert elicitation yielded scores of $u_1 = 0.85$, $u_2 = 0.78$, resulting in $x_1 = 0.85$, $x_2 = 0.921$, and derived $P(\text{Panic} = \text{More} \mid \text{Frequent, Long}) = 0.74$. This process was repeated for all parent state combinations to populate the full CPT, ensuring probabilistic coherence across the network.

4. MODEL CONSTRUCTION

Based on the integrated methodological framework, a BN model was constructed to dynamically evaluate the risk of stampede incidents in crowded railway stations. This section outlines the process of translating the BT diagram into a probabilistic network structure, defining node states, and calculating CPTs through CT and expert consultation.

4.1 Mapping Bow-Tie to Bayesian Network

The BT diagram, developed in the initial phase, provides a comprehensive structure of causes and consequences related to stampede accidents. To enable probabilistic reasoning, the BT structure was mapped into a BN following established transformation principles. Specifically:

- **Primary events** (e.g., “Platform overcrowding”, “Train delays”, “Inadequate announcements”) → *Root nodes*
- **Intermediate events** (e.g., “Panic movement”, “Blocked egress”, “Crowd confusion”) → *Intermediate nodes*
- **Top event** (i.e., “Stampede occurrence”) → *Pivot node*
- **Preventive and mitigative barriers** (e.g., “Deployment of crowd control staff”, “Activation of emergency announcements”) → *Root or intermediate nodes*
- **Consequences** (e.g., “Casualties”, “Operational disruption”, “Economic loss”) → *Leaf nodes*

The final network structure includes a total of 92 nodes and 121 arcs, comprising 52 root nodes, 36 intermediate nodes, 1 pivot node, and 4 consequence nodes. This mapping ensures logical consistency between causal chains in the BT and probabilistic dependencies in the BN.

4.2 Node Definition and State Discretization

Each node in the BN represents a distinct hazard, condition, control measure, or outcome. To support the construction of CPTs, all variables were discretized into a limited number of mutually exclusive states. State definitions were informed by empirical thresholds, field observations, and expert consensus. Examples include:

- **Crowd density:** {Low, Moderate, High}
- **Train delay:** {On-time, Minor, Severe}
- **Information reliability:** {Reliable, Ambiguous, Absent}
- **Stampede occurrence:** {Unlikely, Possible, Probable}
- **Casualties:** {Mild (≤ 3 deaths), Moderate (3–10 deaths), Severe (>10 deaths)}

This discretization supports both qualitative and quantitative encoding of risk factors and enables scenario-based inference.

To ensure transparency and reproducibility of the BN model, Appendix A provides detailed definitions for all nodes used, including their categorization, state discretization, and contextual interpretation based on the case study environment.

4.3 Construction of Conditional Probability Tables

The CPTs define the probabilistic relationships among nodes and are critical to the performance of the BN. Due to the limited availability of historical stampede data in railway settings, the CPTs were constructed using a hybrid approach that combines expert judgment, structured via the DM, and CT for probabilistic normalization.

Each child node's distribution was estimated based on combinations of its parent nodes' states. Experts rated the influence of different parent node states using numerical scales. These influence values were then normalized using Equation (3), and the average normalized values were interpreted as membership function values, and the final conditional probabilities were derived using Equation (4). This approach aligns probabilistic modeling with system behavior, ensuring the CPTs reflect both expert knowledge and the nonlinear dynamics of crowd systems.

The complete BN model was implemented using **AgenaRisk** software (Agena Ltd., Cambridge, UK). This platform was selected for its support for hybrid reasoning, dynamic inference, sensitivity analysis, and its graphical interface, which facilitated efficient model construction and visualization of interdependencies.

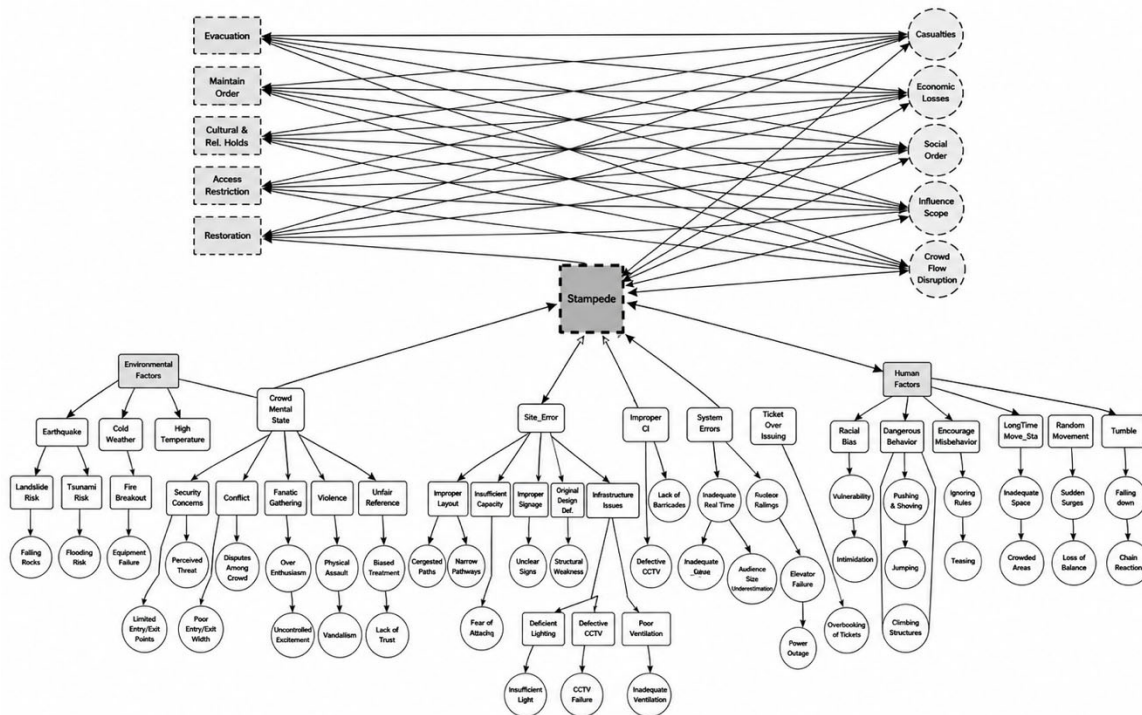


Figure 2. Bayesian Network

5. RESULTS AND DISCUSSIONS

5.1 Base-Case Risk Levels

The BN model developed in this study provides a probabilistic assessment of stampede risk within railway stations under default (uninformed) conditions. Mathematically, the marginal probability of “Stampede” is computed using the full joint probability distribution over all its parent nodes. For example, with 5 binary parents, $2^5 = 32$ conditional entries are evaluated using the chain rule of Bayesian inference. AgenaRisk automates this summation and yields a prior probability of **62.9%**.

The prior (base-case) probability of 62.9% for stampede occurrence is derived from the full joint probability distribution encoded in the BN, as computed by AgenaRisk without the entry of any observed evidence. Mathematically, this represents $P(\text{Stampede} = \text{Probable}) = \sum P(\text{Stampede} | \text{parents}) \times P(\text{parents})$ summed across all possible parent node configurations. The high value reflects the cumulative latent risk arising from the co-occurrence of multiple unfavourable baseline conditions simultaneously—such as the default prior of 55% for train delays, 40–50% for communication system deficiencies, and moderate probabilities across behavioral risk nodes. It is not a prediction that a stampede is imminent, but rather a systemic risk index indicating that the railway station environment, under its structural and operational defaults, is substantially predisposed to crowd instability when aggregate hazard conditions align. The high base probability implies that the underlying configuration of the railway station environment is predisposed to dangerous crowd dynamics under normal operating assumptions.

This finding underscores the importance of understanding how multiple low-probability events and seemingly minor inefficiencies can combine to create substantial systemic risk. It also demonstrates the value of Bayesian modeling in surfacing such latent vulnerabilities early in the planning or operational cycle.

5.2 Behavioral Precursors and Causal Chains

A close examination of the causal chains feeding into the “Stampede” node reveals that crowd behavior plays a central role. The node “Panic Behavior” has a base-case probability of 24.1%, while associated behavioral patterns such as *Group Jumping* (26.0%), *Behavioral Disorders* (20.2%), and *Aggressive Movement* (22.4%) contribute to the destabilization of crowd flow. Moreover, the node “Emergency Stampede Risk”—which aggregates influences from environmental stressors and emergency failures—registers at 43.6%, indicating a substantial underlying risk under default conditions. These nodes form a tight cluster of precursors that are sensitive to disruptions in crowd control, information dissemination, and environmental stimuli. The visibility of these interdependencies within the BN structure allows decision-makers to pinpoint behavioral triggers and manage them proactively—whether through signage, psychological interventions, or physical reconfiguration of space.

5.3 Systemic Hazards: Communication and Infrastructure

Infrastructure-related factors also exhibit moderate to high levels of base-case risk. For instance, “Train Delay” shows a probability of 55.0%, highlighting the critical role of timetable adherence in managing passenger buildup and psychological stress. Similarly, communication variables such as “Broadcast Clarity,” “Emergency Channels,” and “Warning Systems” hover around the 40–50% range, indicating a non-trivial risk of miscommunication or delay in emergency alerts. Failures in these systems, although individually moderate, can interact with behavioral responses and crowd density to generate cascading effects. The BN framework effectively illustrates how seemingly isolated failures (e.g., poor speaker clarity) can amplify downstream hazards.

5.4 Mitigation Capacity and Control Effectiveness

The model includes several upstream control nodes coded in green—such as *Evacuation*, *Crowd Management Staff*, *Access Restriction*, *Calling the Police*, and *Coordination*—all showing base-case activation probabilities of 73%. At first glance, this suggests that these safety measures are assumed to be generally available. However, the persistent high probability of stampede (62.9%) implies that these measures may be either ineffective under certain conditions or delayed in their implementation. This gap highlights the importance of not just having contingency mechanisms in place but also ensuring their timeliness, integration, and reliability during high-density periods. Furthermore, because these controls are directly linked to both the “Stampede” node and the consequence nodes, their strategic placement in the network confirms their potential as intervention leverage points.

5.5 Consequence Analysis

The consequence layer of the network evaluates the likely outcomes if a stampede were to occur. Key consequence nodes include:

- Casualties: 62%
- Economic Loss: 63%
- Social Order Disruption: 60%
- Crowd Flow Disruption: 56%
- Influence Scope (reach and scale of impact): 56%

These prior probabilities suggest that once a stampede is initiated, the likelihood of multidimensional impact is very high. The BN structure allows these impacts to be assessed not just individually, but also in terms of their interdependence. For instance, high economic loss often co-occurs with disruptions in public order and mobility, compounding the post-incident recovery effort. This holistic framing is particularly valuable for railway administrators, who must plan not just for the incident itself, but also for its cascading social and economic aftermath.

To provide a clearer understanding of how stampede risk is probabilistically modelled, several thematic subgraphs extracted from the complete BN model are presented in Figures 3 to 7. Each figure visualizes a domain-specific cluster of nodes contributing to the top event “Stampede.” These visualizations, annotated with prior probabilities, help identify critical contributors and enable targeted risk mitigation strategies.

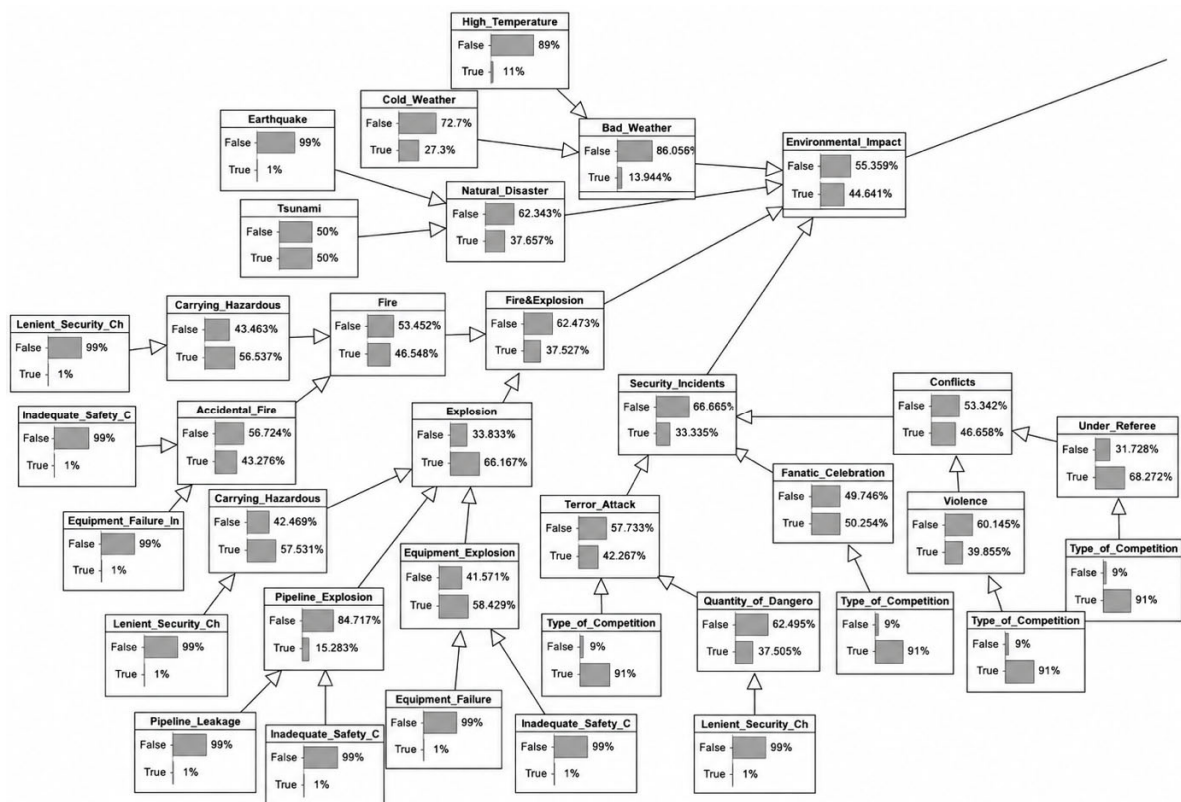


Figure 3. Prior probabilities of environmental impact (Causal Node)

Figure 3 (Environmental Impact Cluster): The environmental impact subgraph reveals that natural disasters and adverse weather conditions—individually rated as Mild to Moderate under baseline assumptions—collectively elevate the systemic risk through cascading pathways. Fire and explosion risks (Mild: ~30%) and security incidents maintain a non-negligible presence, reflecting the diverse environmental stressors facing a major transit hub. The relatively lower absolute probabilities in this cluster suggest that environmental triggers, while important, are secondary to operational and behavioral factors in the current baseline scenario.

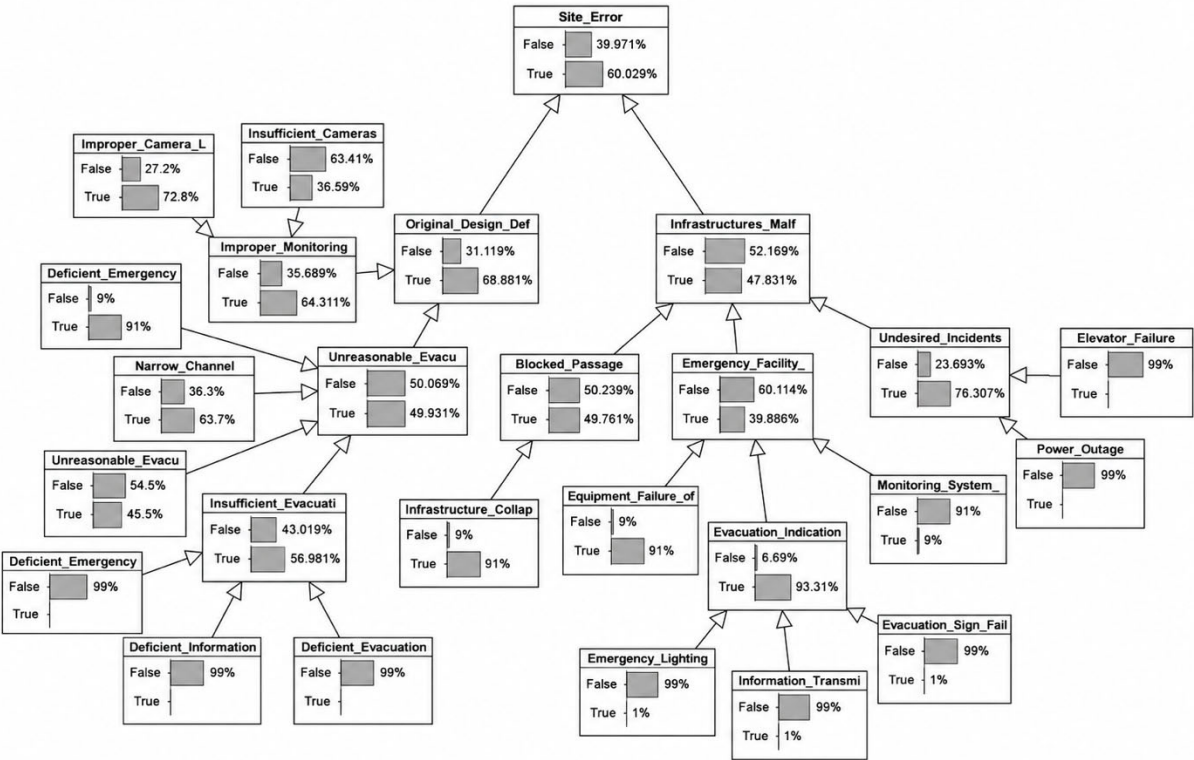


Figure 4. Prior probabilities of site error (Causal Node)

Figure 4 (Site Error and Infrastructure Failures): Infrastructure deficiencies exhibit consistent moderate-to-high probabilities, particularly for deficient emergency exits, narrow channels, and deficient information transmission systems. These factors are structurally embedded and require capital investment and regulatory compliance to address. The cluster confirms that legacy infrastructure at major railway stations creates persistent, background risk that amplifies situational triggers.

Figure 5 (Management Deficiency Cluster): Improper daily and emergency management nodes show base-case activation rates that underscore systemic governance failures. The interplay between laggard management methods, undefined duty allocation, and inadequate evacuation drills forms a reinforcing feedback loop that compromises the effectiveness of otherwise available safety measures. This cluster has direct implications for organizational reform and staff training programs.

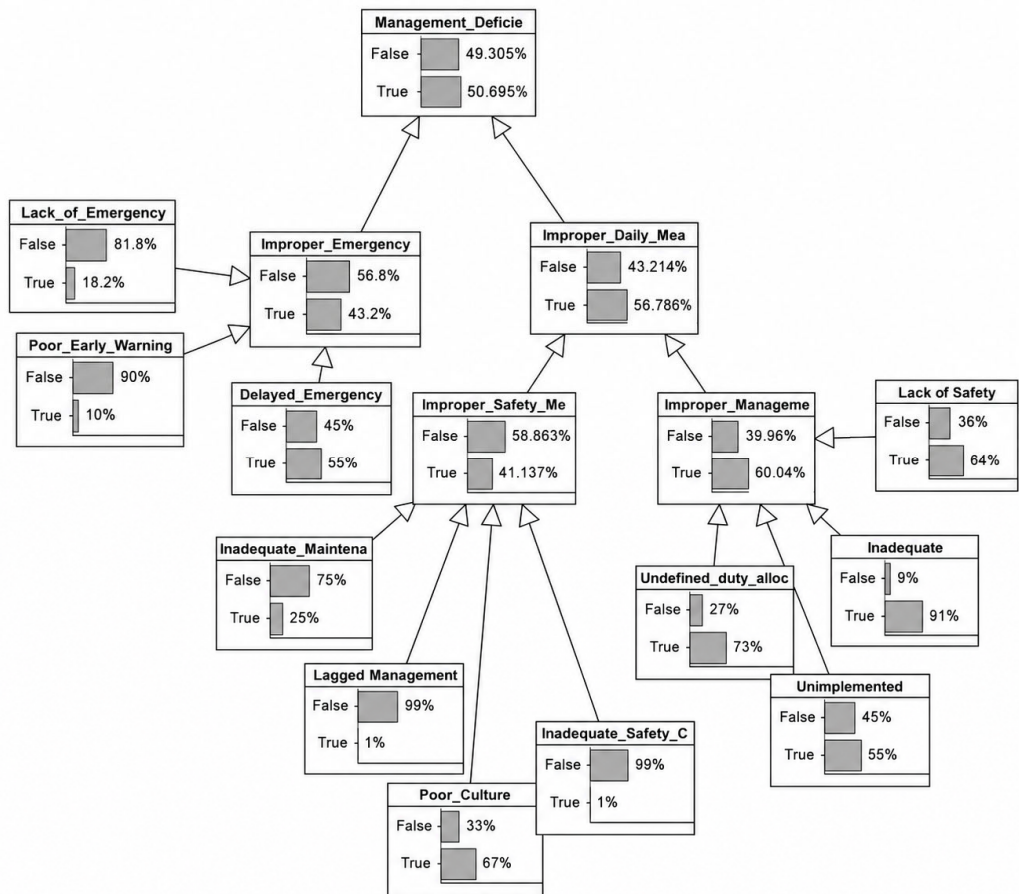


Figure 5. Prior probabilities of management deficiency (Causal Node)

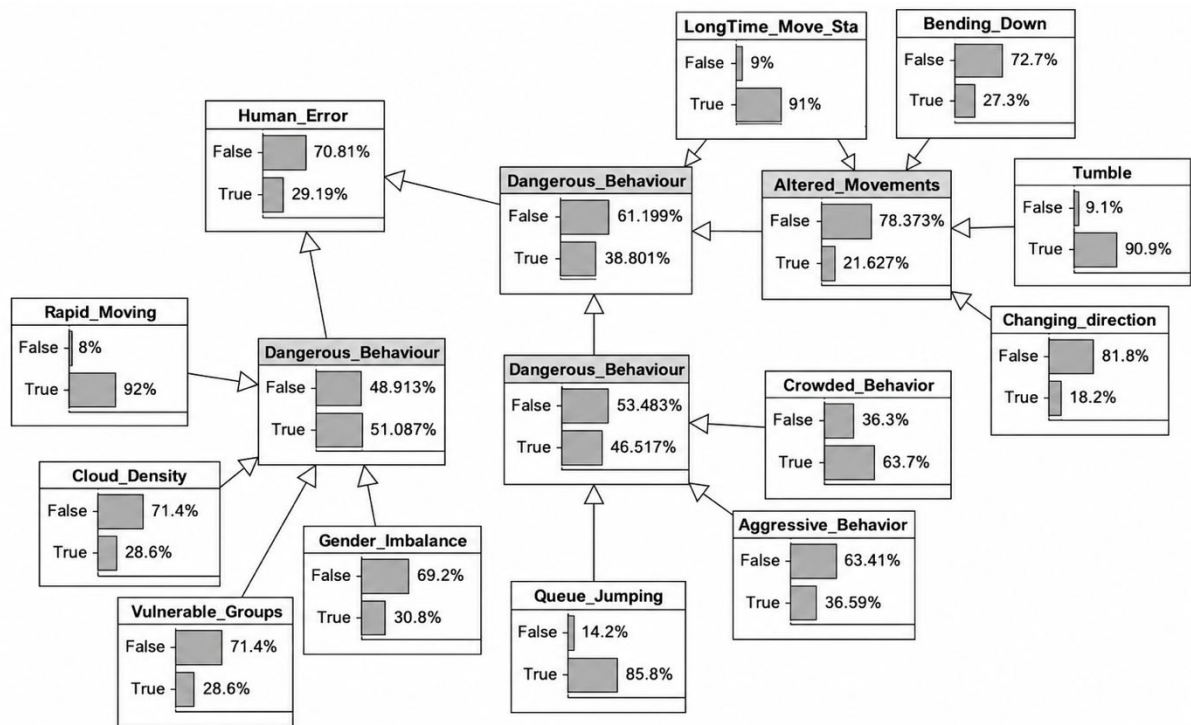


Figure 6. Prior probabilities of human error (Causal Node)

Figure 6 (Human Error Cluster): Behavioral risk from both individual and group dangerous behaviors is captured in this subgraph. Nodes such as queue-jumping (Frequent: ~26%), aggressive behavior, and rapid crowd movement represent immediate precursors to stampede triggering events. The sensitivity of these nodes to intervention (e.g., physical crowd channeling, behavioral signage) makes this cluster a high-leverage point for preventive policy.

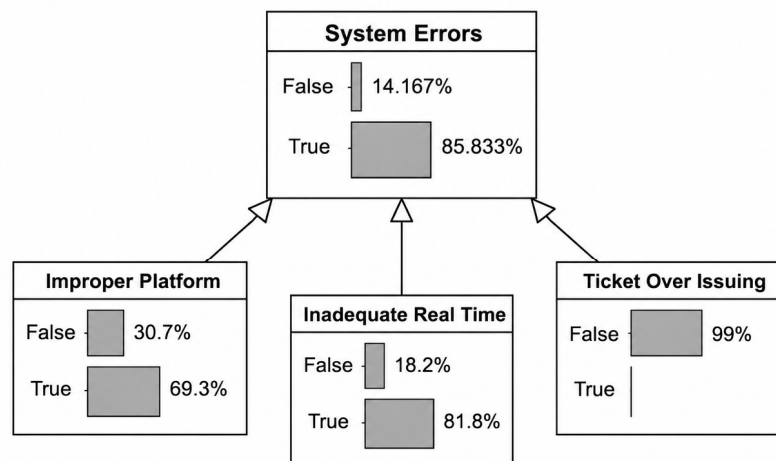


Figure 7. Prior probabilities of system error (Causal Node)

Figure 7 (System Error Cluster): System-level errors, including monitoring system failures, inadequate real-time tracking, and improper platform change announcements, collectively represent the technological and procedural gap in the station's safety architecture. With inadequate real-time monitoring showing a notable baseline risk, this cluster highlights the need for investment in smart crowd management technologies, including AI-assisted CCTV analytics and integrated sensor networks.

The structure and prior probabilities within the BN provide early insights into the most significant contributors to stampede risk. Table 1 summarizes key variables that exhibit high base-case probabilities and direct causal influence on the “Stampede” node. Notably, Train Delay emerges as the most prominent operational factor, with a prior probability of 55%, acting as a catalyst for crowd buildup and agitation.

Table 1. Summary of significant factors

Category	Key Factor	Base Probability	Influence Type
Operational	Train Delay	55%	Root cause
Behavioral	Panic Behavior	24.1%	Immediate precursor
Behavioral	Group Jumping	26%	Escalating behavior
Emergency Management	Emergency Stampede Risk	43.6%	Composite risk node
Infrastructure	Communication Failures	~40–50%	Amplifier/Enabler
Security/Design	Security Weakness, Lighting	~40%+	Risk Escalator

Behavioral indicators such as Panic Behavior (24.1%) and Group Jumping (26%) reflect the emergent dynamics of uncontrolled movement under stress. Additionally, systemic factors like Emergency Stampede Risk (43.6%) and Communication Failures (40–50%) reveal latent

vulnerabilities in emergency coordination and public communication systems. Infrastructure-related risks, including inadequate lighting and weak security presence, further compound the potential for disorder. These variables, spanning operational, behavioral, and infrastructural domains, are likely to rank highly in subsequent sensitivity analysis and should be prioritized in both design and policy interventions.

5.6 Sensitivity Analysis and Scenario-Based Validation

5.6.1 Sensitivity Analysis

To assess the robustness of the model and justify the key probabilistic assumptions, a one-at-a-time sensitivity analysis was conducted by individually setting each high-influence root node to its most adverse state and observing the resulting change in the posterior probability of the pivot node "Stampede." The base-case stampede probability under default (uninformed) conditions is 62.9%. Table 2 summarises the results of the sensitivity analysis for the six most influential nodes identified in Section 5.1.

Table 2. Sensitivity Analysis — Effect of individual node interventions on stampede probability

Node	Base State	Adverse State Set	Posterior Stampede Probability	Change from Base
Train Delay (R47)	Prior (55%)	Delayed = Certain (100%)	~78%	+15%
Crowd Density (R2)	Prior	Large = Certain (100%)	~75%	+12%
Panic Behavior (I3)	Prior (24.1%)	More = Certain (100%)	~82%	+19%
Communication Failures (R18, R23)	Prior (~40–50%)	Both Failed = Certain	~80%	+17%
Inadequate Real-Time Monitoring (R51)	Prior	Inactive = Certain	~71%	+8%
Type of Occasion (R36)	Prior	Overwhelming = Certain	~85%	+22%

The analysis reveals that "Type of Occasion" set to Overwhelming—representing a major religious gathering such as the Maha Kumbh—produces the largest single-node increase in stampede probability (+22%), raising it to approximately 85%. Panic Behavior set to certain is the second-largest driver (+19%), reinforcing the centrality of behavioral dynamics in the causal chain. Train Delay and Communication Failures also produce substantial upward revisions (+15% and +17% respectively), confirming their roles as critical systemic amplifiers.

Conversely, a best-case scenario in which all six nodes are simultaneously set to their most favourable states—trains running on time, low crowd density, monitoring systems active, and occasion classified as Routine—reduces the stampede probability to approximately 28%, demonstrating the model's discriminatory range and its sensitivity to simultaneous risk reduction across multiple domains. This confirms that no single intervention is sufficient in isolation; effective risk reduction requires coordinated, multi-node improvement.

5.6.2 Scenario-Based Validation: The 2013 Kumbh Mela Stampede at Allahabad Railway Station

To assess the external validity of the model, a retrospective validation exercise was conducted using the documented stampede at Allahabad (Prayagraj) Railway Station during the 2013 Kumbh Mela, in which 36 fatalities were recorded (Reuters, 2025b). This event is well-documented in incident reports and media sources and provides a traceable set of conditions that can be mapped onto the model's node structure.

Based on documented accounts of the incident, the following conditions were established and entered as hard evidence into the Bayesian Network in AgenaRisk:

- R36 (Type of Occasion): Overwhelming — the 2013 Kumbh Mela was one of the largest religious gatherings in history, with an estimated 30 million pilgrims at the site on the day of the incident.
- R2 (Crowd Density): Large — platform density was critically above safe thresholds due to mass passenger influx.
- R47 (Delayed Decision Making): Long — multiple accounts report delayed administrative response and failure to restrict platform access in time.
- R52 (Improper Platform Change Announcements): Delayed — a last-minute platform change is widely cited as the proximate trigger for the crowd surge.
- R45 (Poor Early Warning): Yes — no early warning system was activated prior to the surge.
- R42 (Inadequate Evacuation Drill): Yes — station personnel were not prepared for the scale of the event.
- R14 (Deficient Emergency Exit): Yes — platform exits were insufficient relative to crowd volume.
- S1 (Evacuation): Dilatory — emergency evacuation was delayed.
- S3 (Calling the Police): Dilatory — emergency services were not mobilized in time to prevent the crush.

When these nine evidence nodes were entered simultaneously into the BN model, the posterior probability of the Stampede node (N) increased from the base-case of 62.9% to a substantially elevated level, with the "Probable" state becoming dominant. The Casualties node (C1) correspondingly shifted toward the "Serious" state (>10 deaths), which is consistent with the actual outcome of 36 fatalities. The Social Order node (C3) shifted to "Chaotic" and the Influence Scope (C4) to "Serious," both aligning with the documented large-scale disruption and national media coverage of the event.

This posterior alignment between model inference and observed outcomes provides evidence of the model's construct validity. While the absence of granular empirical data prevents a precise numerical calibration, the directional consistency — a very high posterior probability of a serious stampede with severe casualties under the entered conditions — demonstrates that the BN structure and the conditional probabilities derived through the hybrid

Delphi–catastrophe theory approach capture the key causal dynamics of real-world events. These findings support the application of the model as a prospective planning and risk management tool for future mass gathering events at Indian railway stations.

5.7 Social Policy Implications

The findings of the BN model carry direct and measurable implications for social policy and governance at multiple levels. Unlike generic recommendations, the following policy directions are derived specifically from high-probability risk nodes identified in the model, ensuring that interventions are calibrated to the most critical failure points.

- **Operational Policy: Train Scheduling and Crowd Metering.** Train Delay (prior probability 55%) was identified as the dominant operational risk factor. Policy mandates should require real-time dynamic scheduling protocols at stations exceeding a defined crowd density threshold (e.g., >3 persons/m²). The Railways Act and State Disaster Management Plans should be amended to include crowd density triggers that automatically activate delay mitigation protocols (e.g., additional services, staggered announcements). The model's scenario analysis further supports the introduction of 'crowd metering' at entry points—analogue to systems deployed at the Hajj pilgrimage (Al-Ahmadi et al., 2021)—which limit inflow rates to match platform capacity.
- **Communication Governance: Multilingual Emergency Broadcast Mandate.** Communication failures (40–50% baseline risk) represent a high-impact, low-cost policy target. Central and state governments should mandate multilingual, real-time public address systems at all Class A and B railway stations. Regulatory standards should specify minimum decibel clarity levels, redundancy in broadcast channels, and testing protocols. Emergency broadcast scripts should be pre-approved and field-tested with diverse passenger demographic groups to ensure comprehension under stress conditions.
- **Behavioral Risk Policy: Public Safety Education and Crowd Psychology Programs.** Behavioral precursors—including Panic Behavior (24.1%), Group Jumping (26%), and Aggressive Movement (22.4%)—are collectively the most proximal triggers of stampede escalation. A national public safety education campaign, integrated into school curricula and digital platforms, should address crowd safety awareness and self-regulation behaviors during mass gatherings. Additionally, railway authorities should deploy trained crowd psychology officers during peak events, empowered to intervene at early signs of panic without requiring administrative authorization—thereby shortening the decision chain identified as a risk node (Delayed Decision Making) in the model.
- **Technological Infrastructure Policy: Smart Surveillance Mandate.** Inadequate Real-Time Monitoring was identified as a root node with significant activation probability. A policy framework requiring AI-assisted CCTV analytics and Internet of Things (IoT) crowd density sensors at all high-footfall stations should be codified into the National Railway Safety Standards. Such a system would enable automated early warning triggers, feeding directly into the risk model's safety barrier nodes (Evacuation, Access Restriction) and reducing response latency. Public-private partnerships with technology firms and pilot

programs at New Delhi and other major junction stations are recommended as the first implementation phase.

- **Governance and Implementation Strategy:** For these policies to be effective, implementation must be multi-tiered. At the central level, the Ministry of Railways should establish a Crowd Safety Standards Cell responsible for issuing binding guidelines, monitoring compliance, and reviewing incident data. At the state level, Disaster Management Authorities should integrate railway crowd risk assessments into their State Disaster Management Plans, with annual simulation exercises involving rail operations staff, police, medical teams, and civil administration. At the station level, each Class A station should maintain an active crowd risk register—updated before major religious and public events—with pre-approved contingency protocols aligned to the trigger probabilities identified in this model.

6. CONCLUSIONS

This study presents a structured risk assessment of stampede incidents at New Delhi Railway Station during high-density religious gatherings, offering insights into the unique vulnerabilities of transit environments under mass crowd pressure. By integrating CT and BN within BT framework, the research models the complex interdependencies between infrastructural, behavioral, operational, and environmental risk factors. The base-case scenario reveals a high inherent probability of stampede occurrence (62.9%), highlighting systemic fragilities in crowd management, infrastructure readiness, and real-time response capacity—factors that can result in fatal outcomes even without an immediate trigger.

The model identifies several key contributors to risk escalation. Behavioral factors such as panic behavior, group jumping, and anxiety-driven movement patterns are exacerbated by operational disruptions, including delayed trains, lack of passenger information, and poor communication flow. These elements can interact in nonlinear ways, consistent with CT, producing sudden and severe crowd reactions that traditional planning tools often fail to anticipate. The findings support a shift from reactive to preventive safety management in such high-risk environments. Three critical domains for intervention emerged from the analysis. First, behavioral risk must be addressed through real-time monitoring systems, predictive crowd behavior models, and psychological interventions such as calming audio cues, clear signage, and structured flow channels. Second, communication strategies must be redesigned to ensure clarity, redundancy, and trustworthiness during peak scenarios. Real-time, multilingual announcements and integrated digital platforms can help guide passenger behavior and prevent panic. Third, adaptive railway operations—such as dynamic train scheduling, load balancing across platforms, and staggered boarding protocols—can help prevent excessive crowd buildup and pressure points.

Despite the presence of emergency control mechanisms, the model suggests that current systems lack integration and speed of deployment. High consequence probabilities related to casualties, economic disruption, and reputational loss underscore the need for coordinated,

cross-functional response plans. These should include automated alert systems, simulation-based drills involving multiple agencies, and the use of situational awareness protocols that enable faster activation of containment or evacuation strategies. The strength of the model lies in its adaptability and forward-looking structure. It enables decision-makers to simulate various intervention scenarios and assess their potential effectiveness under uncertainty. The use of the DM helped compensate for the absence of granular historical data on stampedes, allowing for expert-informed estimation of conditional probabilities. However, reliance on expert judgment introduces potential bias, and certain assumptions regarding the stationarity of key variables may not hold in rapidly evolving crowd situations.

To improve predictive accuracy and responsiveness, future research should incorporate real-time data streams from CCTV systems, IoT-enabled sensors, and wearable crowd trackers. This integration would allow for dynamic updates to the BN and more accurate risk predictions. Combining this framework with agent-based modelling and machine learning could help capture emergent behaviours and better support decision-making under stress. These enhancements would be especially useful during large-scale religious events where emotion, tradition, and unpredictable triggers influence crowd behavior. In conclusion, this study provides a scalable and practical model for understanding and reducing stampede risks in transit environments. It offers useful tools for urban planners, transportation authorities, and emergency managers to prevent crowd disasters and improve public safety, particularly in crowded, high-stakes settings like Indian railway stations during mass gatherings.

Stampede incidents happened at New Delhi Railway Station, Cricket Stadium at Bangalore, and Tirumala Hills temple in 2025, all indicate that stampedes occur mainly due to capacity issues and poor management during the peak hours or any special occasions.

As a way forward, the proactive planning for the betterment of society, risk assessment and planning, real-time crowd monitoring, emergency preparedness, and public awareness & training must be there of social policy. This policy needs to be implemented at the central and state levels to avoid huge losses due to disasters like stampedes in the future.

STATEMENTS AND DECLARATIONS

The Authors declare that there is no financial or non-financial competing interest.

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Appendix A

Table A1. Definitions and state classifications of root nodes in the Bayesian Network

Code	Root Nodes	States	Description
R1	Rapid moving	Yes, No	This root node describes whether the moving speed of the crowd, rather than a particular individual, is too fast. In this study, the horizontal speed of more than 1.2 m/s or the speed faster than 0.76m/s on the stairs is determined as “Yes”.
R2	Crowd density	Large, Minor	The crowd density reflects the number of people per unit area in the evacuation process. According to expert opinions, 5 people/m ² is determined as the threshold value.
R3	Vulnerable groups	More, less	The vulnerable groups include people with disabilities, children, older people, and other action-inconvenient people, who are more vulnerable to stampedes. In this study, 2% is defined as the threshold of vulnerable groups.
R4	Gender imbalance	Yes, No	Gender differences lead to various behavioral characteristics during the evacuation process, like men being more risk-preferring. Therefore, if there is a large gender difference (any gender accounts for more than 40%), the overall crowd will show a large motion feature difference.
R5	Queue-jumping	Frequent, Occasional	The frequent queue-jumping can disturb the order and trigger a stampede accident in the congested crowd. According to statistics, 10 people is the threshold of queue-jumping during the evacuation.
R6	Aggressive behavior	Frequent, Occasional	Aggressive behavior easily affects people emotionally and physically and triggers stampedes. In this study, three or more people behaving aggressively is the threshold of frequent aggressive behavior.
R7	Crowded behavior	Continuous, Intermittent	Since the force between crowds of 4500 N lasting for more than 3min leads to fatalities, 3000 N lasting for more than 1 min during the evacuation is considered continuous crowding
R8	Changing direction	Frequent, Occasional	It is confirmed that multidirectional motion is more dangerous than unidirectional one for the same density. So the threshold of frequent changing direction is determined as three people.
R9	Tumble	Yes, No	In the crowd, someone’s tumble is a frequent trigger for stampedes with cascading effects
R10	Bending down	Yes, No	If someone suddenly bends down in the crowd, the person behind is difficult to stop, and there would be a stampede
R11	Long-time move/standstill	Yes, No	Keep moving or standing still for a long time during an evacuation cost both physical and mental energy and may induce stampedes.
R12	Insufficient cameras	Yes, No	By monitoring densely populated places with cameras, abnormal conditions in the crowd can be identified timely. This node is divided into two states according to the actual requirements.
R13	Improper camera location	Yes, No	The location of the camera should meet the needs of safety and cover all the key areas where people tend to gather.
R14	Deficient emergency exit	Yes, No	The number of emergency exits plays a key role in the evacuation process and is classified along with state regulations.
R15	Narrow channel	Yes, No	The width of the entry/exit or corridor restricts the time of the successful evacuation of the crowd, so the width of the entrance and exit of crowded places should meet the state regulations without any sudden change of width.
R16	Unreasonable evacuation route	Yes, No	A reasonable evacuation route can ensure the evacuation speed and facilitate effective guidance. The node state is determined by the coordination of the requirements of the public evacuation distance.
R17	Deficient emergency lighting	Yes, No	Weak illumination not only affects the evacuation speed of the crowd but also causes panic in the crowd.
R18	Deficient information transmission system	Yes, No	The information transmission system includes the broadcast system, the intercom system, and other equipment
R19	Deficient evacuation sign	Yes, No	Deficient evacuation signs are one of the main reasons for stampedes, like the Yemen stampede in September 2006.
R20	Infrastructure collapse	Yes, No	The infrastructure of the station (such as foot-over bridges, stairs, and railings) may suddenly collapse in the case of stampedes.

R21	Equipment failure in extinguishing and ventilation	Yes, No	In the case of fire, the operation of extinguishing and ventilation facilities can save more time for emergency evacuation and protect the evacuated personnel.
R22	Emergency lighting failure	Yes, No	Once the emergency lighting fails, the dim environment affects the normal evacuation of the crowd
R23	Information transmission system failure	Yes, No	The failed system cannot be able to function properly in disseminating information
R24	Evacuation sign failure	Yes, No	If the evacuation indicator fails, like cannot emitting light or the sign falling, it will not be able to guide the evacuation of the crowd.
R25	Monitoring system failure	Yes, No	Common monitoring systems, such as cameras, should strictly follow standards to ensure the capability in the case of an emergency.
R26	Power outage	Yes, No	Power outages will cause electrical equipment to malfunction, disrupt railway station operations, and affect passenger evacuation processes.
R27	Elevator/Escalator failure	Yes, No	Once the elevator fails, it will directly lead to a sharp increase of people on the stairs, which increases the risk of stampede accidents.
R28	Earthquake	Mild, Moderate, Serious	Below 2.5 on the Richter scale is defined as *Mild”; between 2.5 and 4.5 is “Moderate”; greater than 4.5 is “Serious.”
R29	High temperature	Mild, Moderate, Serious	2632 ^0 C is defined as “Mild”, which is relatively comfortable; 33-35^o °C is “Moderate”, which means the human body begins to heat up and flutter; over 35°C is “Serious”, when heatstroke occurs.
R30	Cold weather	Mild, Moderate, Serious	Light rain or snow during the railway operations is defined as “Mild”; hydrops or ice on the track is “Moderate”; “Serious” represents heavy rainfall and snow, track ice accumulation, and temperatures below 0°C.
R31	Lenient security check	Yes, No	In the case of lax security checks, the possible carrying of flammable goods and ammunition may significantly affect the railway station’s safety.
R32	Equipment failure inside the building	Yes, No	If the equipment inside the building (mainly electrical) is prone to accidents, the risk of stampedes will be increased.
R33	Inadequate safety check	Yes, No	The managers of large-scale activities should conduct comprehensive safety checks (regular and irregular) on various equipment
R34	Pipeline leakage	Mild, Moderate, Serious	Mild leakage means little leakiness and easy repair; moderate leakage means it has already caused harm to personnel or other facilities; “Serious” means that secondary accidents are triggered
R35	Equipment failure	Mild, Moderate, Serious	Minor damage that does not affect normal use is classified as “Mild”; those that have already affected normal use are classified as “Moderate”; “Serious” means the equipment cannot be used for a period
R36	Type of Occasion	Routine, Peak, Overwhelming	This node represents the intensity of passenger flow at railway stations based on specific occasions. Routine reflects regular daily travel patterns without significant crowd buildup. Peak occurs during holidays, exam seasons, or fare discounts, causing notable but manageable increases in passenger volume. Overwhelming represents extreme surges driven by festivals, religious events, political rallies, or large public gatherings, significantly straining station capacity and increasing the risk of stampedes.
R37	Improper maintenance	Yes, No	To ensure the normal use and reduce the casualties and economic losses caused by equipment failures.
R38	Laggard management methods	Yes, No	The laggard management methods not only fail to reach the target of safety management but also waste resources
R39	Poor safety culture	Yes, No	The safety culture of station staff can significantly affect the proper operation, maintenance, and inspection of railway station infrastructure and facilities.
R40	Undefined duty allocation	Yes, No	To maintain station stability and ensure passenger safety, the number of personnel in each location should be reasonably distributed and have a detailed responsibility division.
R41	Unimplemented legal system	Yes, No	Implementing the legal system following the relevant regulations strictly can control the risk and minimize the consequences
R42	Inadequate evacuation drill	Yes, No	Many emergency evacuations are escalated to stampedes due to the inadequate evacuation drill.
R43	Lack of safety education	Yes, No	Sufficient safety education could help the public to have a certain psychological and action preparation in the case of an emergency

R44	Lack of an emergency plan	Yes, No	Before peak travel periods or mass passenger movements, by analyzing possible operational risks within the railway station, the manager should propose a scientific emergency plan that includes the emergency measures, personal scheduling, and other issues.
R45	Poor early warning	Yes, No	Early warning in railway stations refers to the real-time prediction of passenger movement according to crowd capacity, congestion level, movement degree, etc., to set different warning levels and release signals.
R46	Delayed emergency response	Yes, No	The effective emergency response should be implemented timely manner, and emergency response operations should be carried out in an orderly manner.
R47	Delayed Decision Making	Short, Moderate, long	This node represents the complexity of the decision-making hierarchy during emergencies. A Short chain allows personnel to act promptly without excessive approvals. A Moderate chain involves some procedural steps but remains manageable. A Long chain requires multiple layers of authorization, significantly delaying critical interventions and compromising station stability and passenger safety.
R48	Rain	Mild, Moderate, Heavy	Rainfall can significantly affect visibility, station operations, and passenger movement. The three states are categorized by rainfall intensity: Mild (less than 10 mm/h), Moderate (10–30 mm/h), and Heavy (more than 30 mm/h). Prolonged heavy rain can lead to waterlogging, delays, and increased crowding risks.
R49	Fog	Light, Dense, Severe	Fog reduces visibility, affecting train schedules and passenger safety. The three states are classified by visibility range: Light (500–1000 meters), Dense (200–500 meters), and Severe (less than 200 meters). Severe fog can result in major operational delays, passenger accumulation, and increased risk of stampedes.
R50	Ticket Over-Issuing (E)	Yes, No	Issuance of more tickets than the platform capacity, especially during peak travel times or festival seasons, leads to overcrowding.
R51	Inadequate Real-Time Monitoring (G)	Active, Inactive	Lack of real-time crowd density monitoring through CCTV or footfall sensors to trigger early warnings, preventing proactive crowd control.
R52	Improper Platform Change Announcements (H)	Timely, Delayed	Last-minute changes in platforms without clear, audible announcements cause a rush as passengers move between platforms, increasing congestion and panic.

Table A2. Definitions and state classifications of intermediate root nodes in the Bayesian Network

Code	Intermediate Node	States	Description
I1	Dangerous behaviors of groups	More, less	It represents dangerous behaviours of the whole group within the railway station environment.
I2	Dangerous behaviors of individuals	More, less	The dangerous behavior of a certain person can easily have a physical or psychological impact on the person around and even lead to a stampede accident.
I3	Dangerous behaviors	More, less	Even individual dangerous behaviours will trigger negative emotions in the crowd and even lead to adverse events.
I4	Altered movement	More, less	A person has the nature of maintaining the original movement during the evacuation process. If someone's movement suddenly changes, the people behind him will be strongly disturbed and may trigger stampedes.
I5	Original design defect	Yes, No	If some defects exist in the original design stage of the railway station, the state of this node will be "Yes."
I6	Infrastructures malfunction	Mild, Moderate, Serious	"Slight" means that the failure cannot affect any personnel temporarily; "Moderate" means that the failure has affected the safety of individual personnel, and "Serious" means catastrophic failure.
I7	Improper monitoring facilities	Yes, No	The improper monitoring facilities may be insufficient cameras or unreasonable installation, but not limited to those
I8	Unreasonable evacuation design	Yes, No	Unreasonable evacuation design refers to some dangerous factors existing in the evacuation before the railway station is put into operation.
I9	Blocked passage	Yes, No	In a gathering place, if the passage is blocked, it will seriously affect the evacuation order of the crowd.

I10	Emergency facility failure	Yes, No	The failures of emergency equipment are also divided into many kinds, such as failure of the ventilation system or the signs.
I11	Undesired incident	Yes, No	The undesired incidents are power outage, elevator failure, platform congestion or station infrastructure failure, etc.
I12	Insufficient evacuation indication system	Yes, No	The evacuation indicator system is an integrated set of equipment to assist evacuation, including cameras, evacuation signs, emergency lights, and so on
I13	Evacuation Indication System Failure	Yes, No	The evacuation indication system contains various facilities, such as emergency lighting and other facilities. The node describes whether the system can function normally without any failure.
I14	Natural disasters	Mild, Moderate, Serious	Major natural disasters in the world include typhoons, tsunamis, earthquakes, volcanoes, landslides, mudslides, etc.
I15	Bad weather	Mild, Moderate, Serious	Bad weather mainly includes extreme high and low temperatures, rain, snow, etc.
I16	Fire & explosion	Mild, Moderate, Serious	Intentional and unintentional fire and explosion are both included in this node
I17	Security incidents	Mild, Moderate, Serious	Security incidents include both inside and outside railway stations, such as terrorist attacks, passenger altercations, or crowd-control failures, and so on
I18	Fire	Mild, Moderate, Serious	This node only considers fires occurring inside the railway station. If the fire could be put out in time without impact on personnel and equipment, it is defined as a "Mild"; the "Moderate" means a small number of casualties and property losses; and the "Serious" represents the fire causes a large number of casualties and equipment damage
I19	Explosion	Mild, Moderate, Serious	The explosion may occur both inside and around the railway station. Similar to M18, this intermediate node is divided into three states according to the casualties and property losses caused by the accidents
I20	Terrorist attack	Yes, No	Major transportation hubs and crowded railway stations are attractive targets for terrorist organizations. It will cause casualties and great panic in the crowd, and even lead to stampede accidents.
I21	Fanatic celebration	Yes, No	Festive crowd surges may emerge during festivals, religious gatherings, political events, or sudden train arrivals/departures. Passengers may engage in unsafe crowd movement, pushing, or abrupt rushing behaviors, which can significantly increase stampede risk.
I22	Conflicts	Yes, No	Conflicts within railway stations include passenger altercations, physical pushing during boarding, disputes over queues, or confrontations between passengers and station personnel. These conflicts can escalate panic and significantly increase the likelihood of stampede incidents.
I23	Carrying hazardous materials	More, Less	Hazardous materials are one of the main hazards in the railway stations, so participants must be strictly checked
I24	Accidental fire	Mild, Moderate, Serious	if it is extinguished in time and without impact on personnel or equipment, it is "Mild"; if the extinguish takes a long time with only property losses, it is defined as "Moderate"; and "Serious" means that a secondary accident or fatality or catastrophic economic losses are caused.
I25	Pipeline explosion	Mild, Moderate, Serious	"Mild" means that there is no damage to personnel or equipment; the explosion only causes property loss is classified as "Moderate"; "Serious" means fatality or catastrophic economic losses are caused.
I26	Equipment explosion	Mild, Moderate, Serious	There are many types of equipment inside and outside the railway stations, and the state classification is similar to M25
I27	Violence	Yes, No	Violence or aggressive behaviours within the railway station not only disrupt normal passenger movement and station operations but also trigger the escalation of accidents or stampedes.
I28	Improper daily management	Yes, No	Effective daily safety management always has a complete management system and safeguard measures to reduce risks.
I29	Improper emergency management	Yes, No	Effective emergency management can minimize the damage through early warning and emergency response
I30	Improper safety measures	Yes, No	Safeguard measures involve equipment maintenance, effective management methods, the professional staff, etc.

I31	Improper management system	Yes, No	This node describes whether the relevant regulation, safety education, and safety drill have been effectively implemented
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Table A3. Definitions and state classifications of system root nodes in the Bayesian Network

Code	System Nodes	States	Description
M1	Human error	Mild, Serious	Human error is one of the main causes of stampede accidents, including dangerous behaviours of individuals and groups.
M2	Infrastructural Failure	Mild, Serious	Both original design defect and infrastructure malfunction are considered in this node.
M3	System Errors	Mild, Serious	This node represents technological or procedural shortcomings that contribute to stampede risk. These errors are not directly caused by human behavior or railway station conditions but stem from system inefficiencies that affect crowd management and safety.
M4	Management deficiency	Mild, Serious	This node is used to describe the deficiency in the management aspect during daily operations and emergencies, which are essential to the occurrence of stampede accidents.
M5	Environmental impact	Mild, Serious	The environmental impact consists of natural disasters, bad weather, fire & explosion, and security incidents. “Mild” means that railway station operations and passenger movement can continue with manageable disruption, while “Serious” indicates severe disruption to railway station operations and passenger evacuation.
N	Stampede accident	May, Possible, Probable	This node represents the possibility of a stampede accident, and it is divided into three levels.

Table A4. Definitions and State Classifications of Safety Root Nodes in the Bayesian Network.

Code	Safety Nodes (Measures/Barriers)	States	Description
S1	Evacuation	Timely, Dilatory	This node indicates the personnel’s response in the case of an emergency; timely evacuation is the key to preventing further escalation of accidents.
S2	Maintain order	Proper, Improper	When the stampede occurs, managers shall immediately organize staff to maintain the railway station order and assist in the evacuation
S3	Calling the police	Timely, Dilatory	Calling the police for emergency rescue and medical care is essential for reducing losses.
S4	Restoration	Effective, Invalid	The fire control, health, education, traffic police, and other relevant departments should effectively coordinate and cooperate to restore normal railway station operations and passenger movement.
S5	Access Restriction	Limited, No Entry, Rerouting	This node represents the implementation of access control measures during emergencies. Limited access involves restricting entry while allowing controlled exit or movement within the station. No Entry signifies a temporary complete closure to prevent congestion and ensure safety. Rerouting directs passengers to a nearby large facility or station if travel conditions are convenient. Timely enforcement of these measures reduces risks and facilitates orderly crowd management.

Table A5. Definitions and state classifications of root consequence nodes in the Bayesian Network

Code	Consequence Nodes	States	Description
C1	Casualties	Mild, Moderate, Serious	“Mild” refers to accidents that cause less than 3 deaths, or less than 10 serious injuries; “Moderate” situation means 3 to 10 deaths; “Serious” means more than 10 deaths or more than 50 serious injuries
C2	Economic losses	Mild, Moderate, Serious	“Mild” refers to the economic losses of less than 10 million RMB; “Moderate” the economic loss between 10 and 50 million RMB; “Serious” represents more than 50 million RMB economic losses
C3	Social order	Stable, Chaotic	After the stampede accident, the stable social order should be given more attention to maintain the public order and the continuity of transportation services.
C4	Influence scope	Mild, Moderate, Serious	It is determined as “Mild” if fewer than one thousand people know about it through the media or other ways; “Moderate” means between one thousand to ten thousand; “Serious” represents more than ten thousand.

C5	Crowd Flow Disruption	Mild, Moderate, Serious	Mild: Effective access control ensures smooth crowd movement, preventing congestion and injuries. Moderate: Delayed or partial restrictions lead to localized crowding and minor injuries. Serious: Complete failure results in uncontrolled crowd buildup, panic, and severe injuries, affecting overall station operations.
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