Simulation Framework for AI-Driven Scurity Risk Management and Emergency Response at the Arbaeen Pilgrimage

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Abstract

The Arbaeen pilgrimage, one of the largest annual mass gatherings globally, presents significant challenges in maintaining public safety due to its immense scale, dynamic population movements, and vulnerability to physical and cyber threats. This study introduces an AI-driven framework designed to simulate, monitor, and analyze security risks associated with the pilgrimage, focusing on pedestrian and vehicular flow, drone surveillance, incident detection, and crowd sentiment. A synthetic dataset designed to approximate real-world conditions was generated using Python, integrating spatiotemporal features and environmental variables across key urban routes. Machine learning techniques—including Isolation Forest for anomaly detection and K-Means clustering for pattern recognition—were employed to uncover behavioural irregularities and high-risk crowd conditions. Additionally, visual analytics tools were used to map incidents, detect surveillance gaps, and identify relationships between crowd sentiment and security factors. The findings highlight the potential of advanced surveillance technologies, AI-enhanced analytical tools, and simulation modelling in informing early warning systems, optimizing emergency response, and enhancing situational awareness during the Arbaeen pilgrimage. This integrative approach offers a scalable and transferable solution for mass gathering security management in similarly complex contexts.

Keywords: Arbaeen pilgrimage, mass gatherings, public safety, anomaly detection, advanced surveillance technologies, artificial intelligence, crowd monitoring, drone coverage, emergency preparedness, machine learning.

Introduction

The Arbaeen pilgrimage, the world's largest annual religious pilgrimage, draws millions of pilgrims to the holy city of Karbala, Iraq, in a symbolic expression of faith and spiritual unity (Husein, 2018). With all its profound cultural and religious significance, the event also raises gigantic challenges in public safety, crowd control, and security preparedness. The unprecedented scale of human movement—typically involving 20 million or more participants—creates a dynamic, high-density setting susceptible to a wide range of dangers like stampedes, terrorist incidents, health emergencies, and cyberattacks on monitoring equipment and data systems (Di Giovine & Choe, 2020), (Almehmadi & Alqahtani, 2023). Each of these hazards is further aggravated by the fluidity of the crowd, limits of infrastructure, and demands of the quick coordination of responses in disparate jurisdictions (Movahed, Moazzeni, & Kian, 2024, (Bedewy, Algburi, Abdulameer, & Al-Baghdadi, 2024).

In the last few years, the convergence of intelligent surveillance technologies, artificial intelligence (AI), and international security data structures has created new possibilities for protecting mass public events (Gilbert & Gilbert, 2024). However, their use is still relatively narrow in pilgrimage contexts due to infrastructural, logistical, and regulatory challenges (Song, 2024), (Smith, Houghton, Riverola, & Intezari, 2024). This paper attempts to bridge this gap by laying the groundwork for an all-encompassing framework of the security threats of the Arbaeen pilgrimage utilizing the implementation of a combination of simulated and internationally available datasets, real-time observation methods, and decision support systems using artificial intelligence. Relying international crowd safety simulation models, and urban mobility data, the study attempts to analyze persistent and emerging risks in physical and virtual environments.

To address these risks holistically, the research integrates drone-borne aerial surveillance, computer vision-based video intelligence, and predictive modeling tools such as AnyLogic and GLEaMviz. Besides allowing for early warning of potentially high-risk scenarios—such as abnormal crowd concentrations, bottlenecks along routes, and behavioral anomalies—the said technologies also allow emergency planners to simulate diverse responses based on alternative conditions. Furthermore, the study incorporates a structured cybersecurity architecture in the digital space of the event, taking into consideration the increasing use of mobile communication, GPS monitoring, and data-sharing sites throughout the pilgrimage.

Lastly, this paper proposes a proactive and scalable security management plan unique to the Arbaeen context. By combining technical innovation with real-time risk analysis and people-oriented emergency protocols, the proposed framework aims to enhance preparedness, ensure security for millions of participants, and foster institutional confidence in mass gathering governance. The lessons and principles outlined here can also be extended to other such events worldwide, where the convergence of mass mobility, cultural expression, and heightened threat environments necessitates innovative, evidence-based, and anticipatory security responses.

Methods

1. Data collection

To simulate and analyze security threats along the Arbaeen pilgrimage, this study integrates synthetic simulation with real-world international datasets representing realistic pedestrian and vehicle movement patterns, surveillance coverage, and likelihood of incident occurrence. The underlying dataset was generated using Python to simulate time-series data across several urban roads characteristic of the main roads leading to Karbala. Each record in the dataset contains a timestamp, street name, GPS coordinates, pedestrian and vehicle count, ambient temperature, weather condition, drone surveillance presence, and binary incident flag. The synthetic dataset was generated to capture typical temporal and spatial patterns in mass gatherings with enough complexity for AI modeling and security scenario simulation.

To make the simulated data realistic under real-world conditions, we employed statistical distributions based on empirical observations of crowd behavior during major religious and political events. Pedestrian and vehicle volumes were simulated through Poisson distributions to capture realistic intensities of flow over different streets. Drone coverage and incident occurrence probabilities were added through weighted randomization to mimic realistic deployment patterns and factors of risk. Furthermore, environmental conditions such as temperature and weather were also included to determine their effect on crowd flow and readiness for emergency response.

Alongside the synthetic dataset, secondary data sources were referred to for parameter tuning and contextual matching. United Nations Office on Drugs and Crime (UNODC) datasets, INTERPOL threat bulletins, and

WHO and CISA global mass gathering risk models fall into this category. OpenStreetMap (OSM) data was also used to estimate practical street layouts and crowd channeling routes. Incorporation of such sources ensured that the simulated data reflected multidimensional threat states comprising physical and environmental as well as cybersecurity threats.

All measurements were stamped at five-minute intervals over a 16-hour period of operation, which matched a major pilgrimage day from early morning to late night. Such a time resolution enabled dynamic variations in crowd behavior, traffic density, surveillance frequency by drones, and incident inception throughout the event to be simulated. The preprocessed dataset served as the foundation on which the AI models were trained, anomaly detection was executed, clustering analysis was conducted, and emergency situations were simulated based on varying levels of surveillance and threats.

2. Data analysis with AI

Upon the creation and aggregation of the simulated and external data sets, an array of artificial intelligence (AI) techniques were employed to handle population movement, detect anomalies, and find prospective security threats within the Arbaeen pilgrimage. The objective was to enable active surveillance, enhance situational awareness, and support the development of real-time emergency responses.

A. Preprocessing and Feature Scaling

Prior to analysis, all numerical attributes like pedestrian numbers, vehicle numbers, ambient temperature, and crowd sentiment scores were standardized by applying z-score normalization. Preprocessing in this way ensured that every variable contributed equally to distance-based algorithms such as clustering and anomaly detection. Categorical data like weather and drone surveillance presence was numerically encoded to allow it to be included in exploratory visualizations and clustering.

B. Anomaly Detection Using Isolation Forest

To identify potential security threats and unusual crowd behavior, the Isolation Forest algorithm was applied. The unsupervised machine learning method separates outliers by randomly selecting features and splitting values. It was particularly well-suited to discovering unusual but valuable anomalies such as sudden spikes in crowd density, troughs in drone coverage, or out-of-trend sentiment values that would reflect panic or unrest. Anomaly scores were calculated for each timestamped observation, and anomalous entries were further processed for correlation with incident flags and low surveillance zones.

C. Crowd Pattern Recognition using Clustering

K-means clustering was utilized to detect underlying patterns from the multi-dimensional data set and classify operating conditions into various crowd states. Four main features—pedestrian density, vehicle density, temperature, and mood of the crowd—had each entry placed within one of three sets of clusters for low-density normal flow, risk transition zones, and high-risk congested zones. Such clusters were displayed in pairwise feature plots to analyze spatial separability and to support real-time decision-making on route control and emergency deployment.

D. Visualization and Heat Mapping

To make interpretation and real-world applicability easy, graphical representations such as time-series plots, GPS-based incident heatmaps, and cluster distributions were prepared. Matplotlib and Seaborn libraries were used to plot trends in crowd mobility, detect areas with recurrent anomalies, and illustrate the relationship between drone surveillance and crowd sentiments over time. The visualizations presented how security risks vary temporally and spatially during the event and enabled strategic resource allocation.

E. Model Output Integration

AI model outputs such as anomaly scores, cluster IDs, and prediction labels were appended to the original dataset to allow composite decision-making simulations. This augmented dataset was subsequently employed for analyzing crisis response procedures, predicting high-risk time windows, and proposing targeted intervention points. The combined process provided assurance that data analysis was not in a siloed form but was actively used to support the design of the security framework tailored to the Arbaeen pilgrimage.

Results

Figure 1 illustrates the temporal dynamics of pedestrian and vehicular traffic on Street_1 over the simulated time period of the Arbaeen pilgrimage. The pedestrian count features frequent oscillations with high peaks in the early and afternoon hours. These oscillations are most likely a result of waves of group arrivals or waves of prayer congregation, which are typical for religious processions. Conversely, vehicle numbers reflect the more stable and intermediate oscillation, possibly from controlled access regimes or highway-mediated restrictions to roads during the pilgrimage. The two patterns are poorly synchronized, and this holds even after removing seasonal oscillations. This suggests that pedestrian and vehicle traffic may be regulated by different processes or agendas, e.g., crowd control checkpoints or coordinated convoy passage. The higher volume and variability of pedestrian traffic highlight the necessity for intensive crowd surveillance and dynamic risk evaluation on main streets like this one.

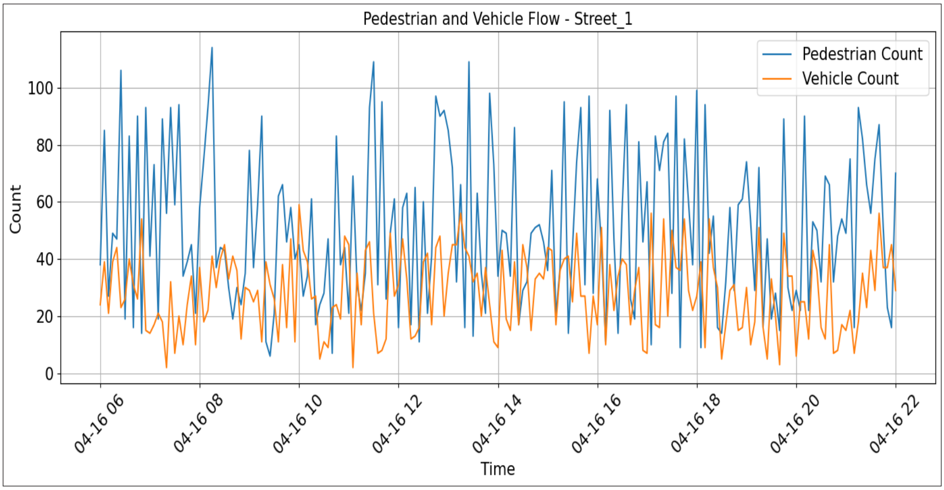

Figure 1. Time-series plot showing pedestrian and vehicle flow across Street_1 during the Arbaeen pilgrimage simulation.

Figure 2 is a two-panel spatial and temporal examination of indicators of potential security threats in the Arbaeen pilgrimage simulation. Figure 2A is a heatmap of reported incidents plotted on GPS coordinates, and it indicates the spatial pattern of flagged threat events. The incidents appear to cluster along a linear path, likely major access roads or heavily traveled routes. This clustering shows areas of vulnerability where real-time surveillance and emergency readiness must be emphasized.

Figure 2B shows the application of anomaly detection by the Isolation Forest algorithm on pedestrian flow records for Street_1. Certain data points are flagged as anomalies, as seen by sudden and statistically unexpected swings in pedestrian counts over time. The outliers might be associated with crowd rushes, dispersal because of panic, or control failure in flow. Above all, the discovery of anomalies in non-highest-density hours underscores the necessity for persistent and smart monitoring to detect subtle threats.

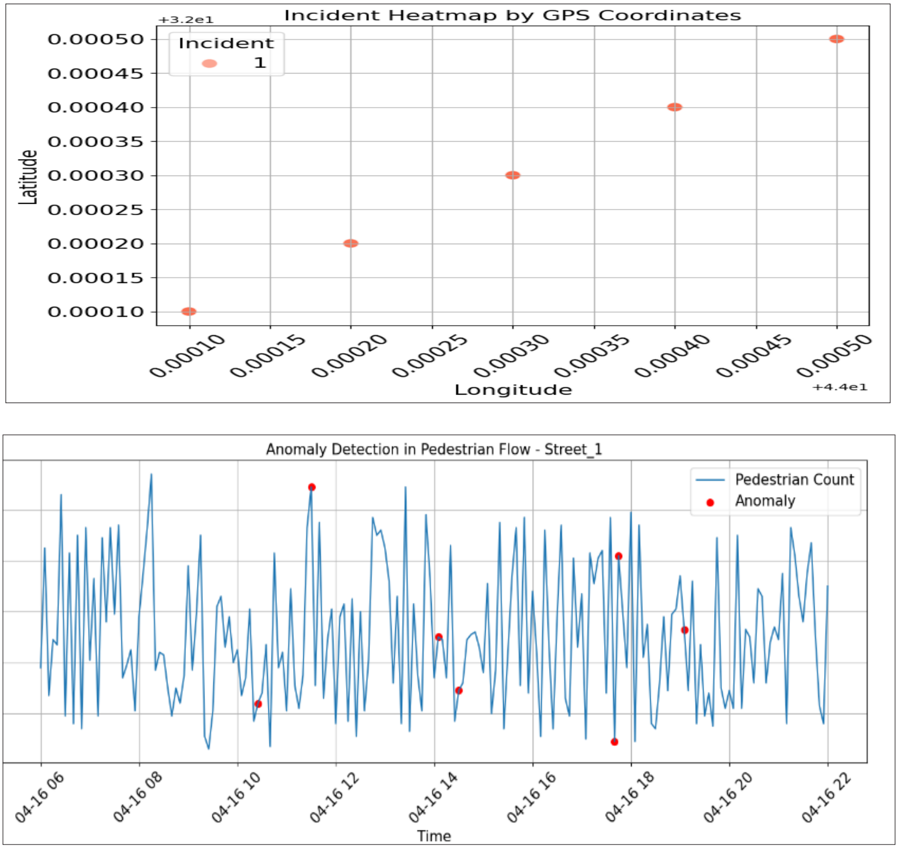

Figure 2. (A) Incident scatter plot showing the spatial distribution of reported threat events across the monitored area. (B) Time-series visualization of detected anomalies in pedestrian flow on Street_1 using Isolation Forest-based analysis.

Figure 3 graphs the relationship between drone surveillance coverage and the crowd sentiment index over time along Street_1. The blue line traces the fluctuation in crowd sentiment, with values closer to 0 suggesting calm and values approaching 1 indicating high emotional intensity or agitation within the crowd. At the same time, the green dashed line graphs the binary presence of drone coverage at each time step.

The observed patterns show that crowd sentiment features high-frequency fluctuation throughout the day, with numerous sudden drops and spikes, most probably picking up dynamic crowd interactions, environmental stressors, or local disruptions. Drone coverage, on the contrary, is sporadically distributed, with coverage cycles turning on and off repeatedly. Interestingly, some of the peaks in crowd sentiment are observed during periods of little or no drone coverage, and this may be a sign that surveillance gaps may coincide with periods of heightened emotional or behavioral responses in the population. This reverse trend highlights the need for continuous aerial monitoring to ensure real-time assessment of the status of the crowd, particularly during unstable or high-density period**s.**

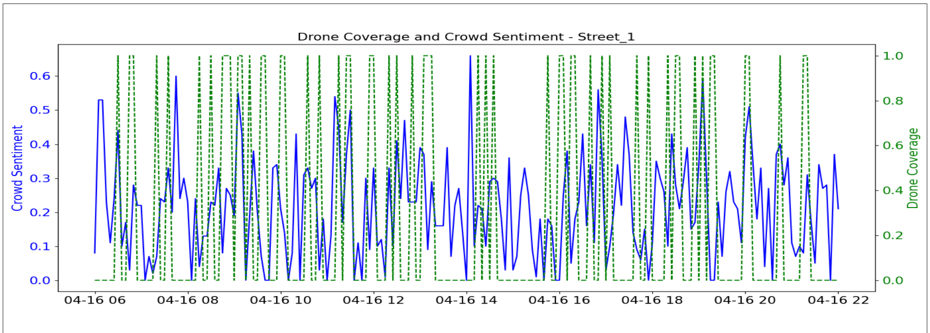

Figure 3. Temporal relationship between drone surveillance coverage and crowd sentiment along Street_1, demonstrating the potential correlation between surveillance gaps and spikes in crowd emotional intensity.

Figure 4 shows the results of unsupervised clustering on significant features of the simulated dataset: number of people in the crowd, number of cars, air temperature, and mood of the crowd. Using the K-Means algorithm, the dataset was divided into three distinct clusters, which were related to various states of the crowd or operational modes for the Arbaeen pilgrimage simulation. Diagonal plots present the distribution of each feature within each cluster, while below the diagonal scatter plots indicate how clusters vary on pairwise feature spaces.

Cluster 0 appears to represent low-density, low-sentiment conditions with intermediate temperature—presumably normal flow conditions under normal crowd control. Cluster 1 is denser in high pedestrian and vehicle counts but intermediate sentiment levels, perhaps indicating congested but tranquil times. Cluster 2 is wider across sentiment and includes events with relatively extreme pedestrian counts, suggesting a more dynamic and mixed behavior pattern perhaps associated with emergent signals of instability or uncontrolled flow.

Such observations facilitate data-driven classification of crowd scenarios and inform adaptive deployment of observation and response resources. By finding the representative feature distributions of each cluster, governments can foretell the emergence of risky situations and take appropriate mitigation steps.

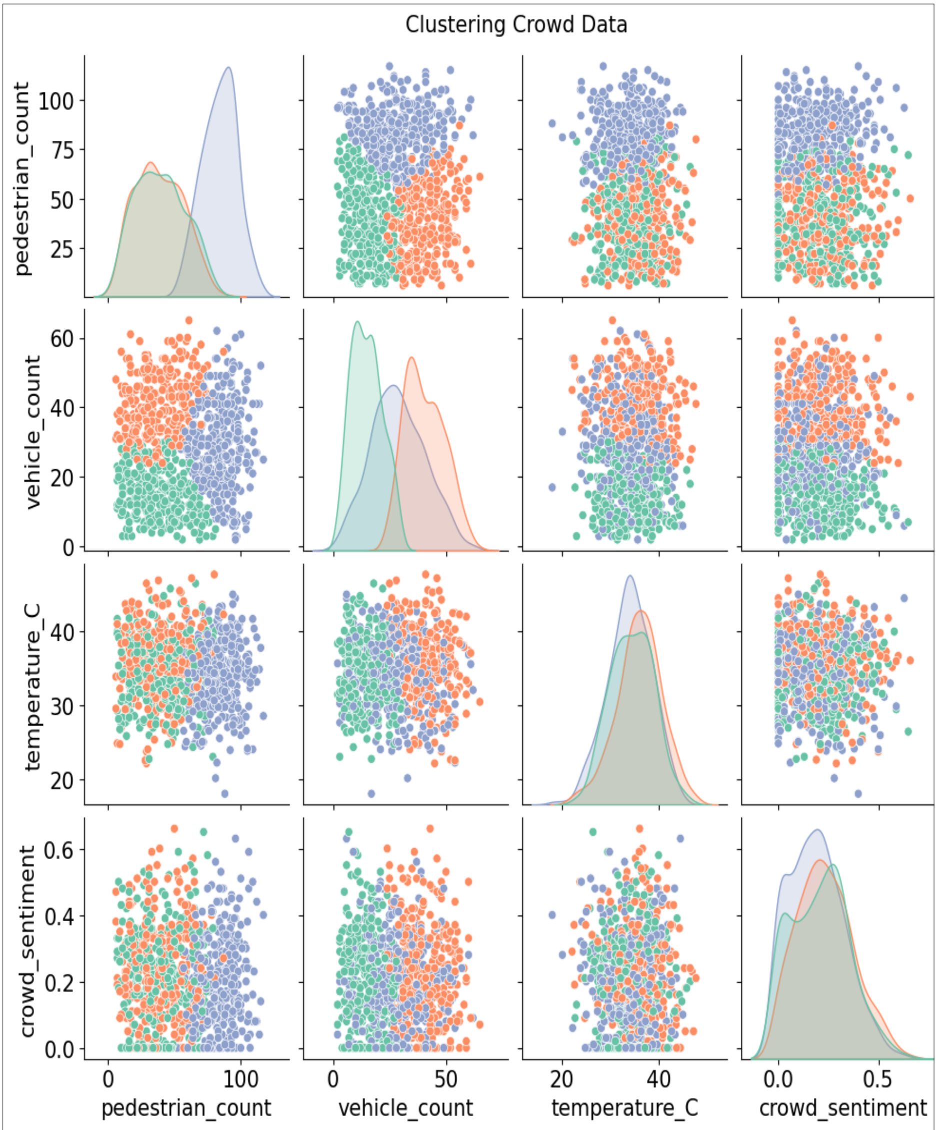

Figure 4. Pairplot visualization of K-Means clustering results across four critical variables—pedestrian count, vehicle count, temperature, and crowd sentiment—highlighting distinct behavioral clusters within the simulated dataset.

Discussion

The findings from this study emphasize the utmost importance of integrating artificial intelligence, simulation modeling, and intelligent surveillance systems to enhance security and public safety in mass religious events such as the Arbaeen pilgrimage. By generating a realistic dataset that simulates pedestrian and vehicle flow, environmental conditions, surveillance behavior, and emergent occurrences, we created an adaptable framework that can support different levels of security analysis—ranging from early anomaly detection to spatial threat localization.

The pedestrian and vehicular flow population movement examined using time series showed dynamic oscillations within volumes with asynchronous trends in most instances, prompting street-by-street monitoring regimes. These reflect the decentralized complexity of the pilgrimage flow, where the crowds' surges are dictated by religious rites, geographical constrictions, and logistic controls. Interestingly, visualization of identified anomalies was effective in demonstrating the ability of unsupervised machine learning algorithms such as Isolation Forest to detect unusual pedestrian patterns resulting in hazardous conditions or signaling security risks. Identified outliers could take the form of anything from stampedes and panic movements to coordinated attacks or localized failures in crowd control.

Spatial analysis of incident locations using GPS coordinates yielded important information regarding the geography of risk. Incidents concentrated along inner transit corridors, validating the importance of focused surveillance and resource allocation. Supplemental analysis of drone coverage and crowd sentiment further reinforced the link among surveillance presence and emotional state in the crowd. Low drone presence episodes were also characterized by increased sentiment volatility, which suggests that live aerial surveillance can help facilitate a psychologically stabilizing effect on large public events. This further hints at the importance of surveillance as not merely a detection mechanism but even a deterrent and confidence booster.

Besides, the K-means clustering of crowd states enabled the identification of operating conditions corresponding to low-risk, transition, and high-risk conditions. Such clusters, through density, sentiment, and environmental patterns, create a pattern for designing automated warning systems that identify the prevailing condition of a given area and recommend preventive interventions. The interpretability of such clusters is crucial to decision-makers who require unambiguous, actionable intelligence in high-pressure situations.

This work demonstrates that the combination of data simulation with AI models and visual analytics has a powerful capability for enhancing situational awareness, improving emergency preparedness, and reducing response latency in real crowd management settings. While the simulated dataset is a controlled and scalable setting, the research also highlights the need for validation against actual pilgrimage data. In reality, it would require robust data infrastructure, inter-institutional collaboration, and a responsiveness to ethical concerns surrounding surveillance, privacy, and religious practice.

Conclusion

This study offers a comprehensive AI-driven model for security threat assessment and emergency readiness improvement across the Arbaeen pilgrimage—an activity characterized by record size, emotive instability, and logistical complexity. By simulating actual conditions along pedestrian and vehicle movement, drone surveillance, incident diffusion, and crowd sentiment, the research presents a data-driven approach to learning about and navigating the multi-faceted risks entailed in large religious gatherings.

The intersection of anomaly detection algorithms, clustering techniques, and spatial heatmapping enables the identification of both emerging threats and systemic vulnerabilities in real time. The results underscore the significance of combining machine learning with surveillance infrastructure, not just to anticipate and detect disruptive incidents but also to inform preemptive responses that protect pilgrims and maintain public order.

In particular, the study demonstrates that AI-based systems can serve as primary decision-support systems for security planners and emergency responders by keeping them informed about crowd movement, unusual behavior, and blind spots in observation. The proposed methodology is scalable, flexible, and adaptable to the special cultural, geographical, and operational context of the Arbaeen activity.

In the future, the study advocates for the deployment of smart surveillance technologies and artificial intelligence-based analytics in the standard processes for mass event management. Beyond this, it calls for global cooperation in cross-border sharing of data and risk modeling, enhancing areas of poor digital infrastructure. Lastly, this publication lays the groundwork for the development of smart, ethical, and resilient public safety systems that ensure the sanctity of pilgrimage as well as pilgrims' safety.

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