Sustainable Pilgrimage Tourism Management: Visitor Flow Modelling for Mecca and Kyoto

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Abstract.

High-density pilgrimage destinations face a tension between accommodating growing visitor numbers and preserving the safety, spiritual quality and heritage value of sacred sites. This paper applies agent-based visitor flow modelling to two high-density pilgrimage destinations, the Grand Mosque precinct in Mecca during non-Hajj Umrah periods and the Fushimi Inari and Kiyomizu-dera pilgrimage corridors in Kyoto, in order to evaluate management measures for reducing congestion. The models represent individual visitors as agents with heterogeneous origins, itineraries, walking speeds, group sizes and responsiveness to information, moving through spatially explicit networks calibrated with pedestrian counts, mobile location data and observed dwell times collected in 2025. Four management measures were tested individually and in combination: time-slot reservation, real-time information nudges delivered through mobile applications and signage, physical route separation, and capacity capping at entrances. Performance was assessed using peak density, mean waiting time, throughput and a satisfaction index derived from survey-based relationships between crowding and visitor experience. Scenario analysis identifies time-slot reservation and information nudges as the most effective measures for reducing congestion without lowering visitor satisfaction, with the combined scenario reducing peak densities by 34 per cent in Mecca and 29 per cent in Kyoto while holding satisfaction within two points of the baseline. Capacity capping reduced density comparably but lowered satisfaction because of extended waiting, and route separation produced modest gains that depended on site geometry. The paper discusses the transferability of measures between destinations with different religious, regulatory and cultural characteristics and proposes a decision framework for sustainable pilgrimage tourism management.

Keywords: pilgrimage tourism, agent-based modelling, visitor flow management, congestion, sustainable destination management

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1. Introduction

Pilgrimage is among the oldest and largest forms of travel, and the sacred sites at its destinations are frequently located in dense historic fabric never designed for present volumes. Mecca receives millions of Umrah pilgrims each year in addition to the Hajj, and Saudi Arabia's Vision 2030 targets 30 million Umrah visitors annually. Kyoto, whose shrines and temples attract both religious visitors and international tourists, has become emblematic of over-tourism in historic districts. In both destinations the management of visitor flows is central to safety, to the quality of the religious and cultural experience and to heritage preservation.

Managing flows at pilgrimage destinations is distinctive. Visitors are motivated by religious obligation, which limits the acceptability of measures that restrict access; peaks are

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tied to religious calendars and prayer times; and the spatial structure of sacred sites is fixed, so that physical expansion is constrained. Managers therefore rely on scheduling, information and routing, whose effects depend on how individuals respond and on crowd–space interactions. Agent-based modelling, which simulates individual visitors and the emergent patterns of crowding, offers a means of evaluating such measures before implementation.

This paper applies agent-based visitor flow modelling to two high-density pilgrimage destinations that differ markedly in religious context, regulatory capacity and visitor composition: the Grand Mosque precinct in Mecca and the pilgrimage corridors of eastern Kyoto. It develops and calibrates models for each, tests four management measures individually and in combination, and evaluates them against congestion and satisfaction criteria. The comparative design allows the study to ask not only which measures are effective but whether their effectiveness depends on the destination context, a question of practical importance for the many sacred sites that look to leading destinations for management models. The paper reviews the relevant literature, describes the modelling approach and data, presents scenario results and discusses implications for sustainable pilgrimage tourism management.

2. Literature Review

2.1 Pilgrimage tourism and sustainability

Research on pilgrimage tourism has moved from debates about pilgrims versus tourists towards the management of sacred sites as destinations serving both. Collins-Kreiner (2010) argues that the blurring of these categories matters for management, since religious visitors and tourists may have different expectations of crowding and behaviour. Shinde (2021) identifies carrying capacity, infrastructure and the commodification of religious experience as recurrent sustainability challenges, noting that religious authorities and tourism agencies often have divergent priorities. Carrying capacity has been applied to Mecca through studies of crowd density during Hajj that established thresholds beyond which movement becomes unsafe (Helbing et al., 2007).

Koens et al. (2018) argue that over-tourism is a matter of the concentration of visitors in time and space and of perceived loss of quality rather than of numbers alone, so that solutions must address distribution. Studies of Kyoto document the concentration of visitors at a few temples and shrines, conflicts with residents over transport and public space, and measures including dispersal campaigns, congestion forecasts and, at some sites, timed admission (Nagai, 2021).

2.2 Visitor flow management measures

The management literature distinguishes demand measures, including pricing, reservation and information, from supply measures such as capacity expansion, route design and flow separation. Reservation systems at parks, museums and heritage sites have generally reduced peak crowding while raising questions of equity and spontaneity (Manning, 2011). Information-based measures, or nudges in the sense of Thaler and Sunstein (2008), depend on the proportion of visitors who receive and act on the information and on acceptable alternatives (Gössling et al., 2019). Route separation and one-way systems have long been used at sacred sites, notably in the Mataf and Masa'a at Mecca, with effects dependent on geometry.

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2.3 Agent-based modelling of pedestrian and visitor flows

Agent-based models simulate individual entities following rules and interacting with one another and their environment, from which aggregate patterns emerge (Bonabeau, 2002). In pedestrian dynamics, the social force model of Helbing and Molnár (1995) reproduces lane formation, bottleneck oscillation and turbulent crowd motion at high densities, and Helbing et al. (2007) applied video analysis and modelling to the Jamarat Bridge during Hajj to identify thresholds that informed redesign. Cellular automata and network-based models offer cheaper alternatives for larger areas and longer horizons.

In tourism research, Itami et al. (2003) developed an early recreation behaviour simulator for trail management, and later studies have modelled visitor itineraries in cities using mobile location data for calibration (Zheng et al., 2017). Behaviourally rich agents on spatially explicit networks allow the evaluation of reservation and information measures, which operate by changing individual decisions, alongside physical measures. Validation remains a challenge and best practice involves calibration against observed counts and sensitivity analysis. The present study extends this tradition to a comparative application across two pilgrimage destinations.

3. Methodology

3.1 Study areas

The Mecca model covers the Grand Mosque precinct including the Mataf, the Masa'a, the prayer halls and the surrounding plazas and access points, an area of approximately 1.2 square kilometres. Modelling focused on Umrah periods outside Hajj, in particular the last ten days of Ramadan, when daily visitor numbers are at their highest. The Kyoto model covers the eastern pilgrimage corridor comprising Fushimi Inari Taisha and its approaches, and the Higashiyama district from Kiyomizu-dera through the Ninenzaka and Sannenzaka lanes to Yasaka Shrine, an area of approximately 2.4 square kilometres with narrow historic streets. Both areas experience severe congestion at predictable times: in Mecca around the five daily prayers and particularly Tarawih and Tahajjud prayers in Ramadan, and in Kyoto during mid-morning and late afternoon in the spring and autumn peak seasons.

3.2 Data

Table 1 summarises the data sources used for model construction and calibration. Pedestrian counts were obtained from automated counters and from the Mecca precinct authority's crowd monitoring system at entrance and corridor points. Anonymised mobile location data aggregated to 50-metre grid cells at fifteen-minute intervals were obtained from a telecommunications provider in Saudi Arabia and from a commercial data vendor in Japan for representative peak periods in 2025. Dwell times at key locations were derived from these data and verified by field observation. Visitor surveys were conducted with 1,240 respondents in Mecca and 980 in Kyoto to establish itinerary patterns, group composition, use of mobile applications and the relationship between perceived crowding and satisfaction, which was modelled as a function of experienced density following the approach of Manning (2011). Network geometry was derived from geographic data and site plans.

Table 1: Data sources for model construction and calibration

Data type	Mecca	Kyoto	Use in model
Pedestrian counts	Precinct monitoring system, 42 points, 2025 Ramadan	Automated counters, 18 points, spring and autumn 2025	Calibration of inflow and validation of link flows

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Mobile location data	Telecom provider, 50 m grid, 15-min intervals	Commercial vendor, 50 m grid, 15-min intervals	Origin–destination patterns, dwell times, validation of densities
Visitor survey	1,240 respondents	980 respondents	Itineraries, group size, app use, crowding–satisfaction function
Field observation	Dwell times and walking speeds at 12 locations	Dwell times and walking speeds at 10 locations	Agent parameters and validation
Network and site data	Site plans and geographic data	Municipal geographic data and site plans	Spatial network, capacities, entrances

Source: Authors' compilation (2025)

3.3 Model structure

Both models were implemented in a network-based agent framework in which agents move along links representing corridors, lanes and open areas discretised into cells, with movement speed on each link a decreasing function of local density based on established pedestrian fundamental diagrams (Fruin, 1971). Agents were generated according to time-varying arrival profiles derived from counts and assigned attributes including origin entrance, itinerary of destinations and intended dwell times, group size, free walking speed and responsiveness to information, drawn from distributions estimated from the surveys. Agents follow shortest-time paths and re-route when local density exceeds thresholds, with the probability of re-routing dependent on their information responsiveness. In the Mecca model, ritual behaviour at the Mataf and Masa'a was represented by fixed circuits with density-dependent speed. Models were calibrated to reproduce observed link flows and grid densities for baseline peak days, with the mean absolute percentage error of hourly link flows at 11.4 per cent in Mecca and 13.2 per cent in Kyoto and densities in the highest-density cells reproduced within 15 per cent. Sensitivity analysis on responsiveness, walking speed and dwell time parameters indicated that scenario rankings were stable across plausible ranges.

3.4 Scenarios and performance measures

Four management measures were specified. Time-slot reservation assigned arrivals to slots that flattened the arrival profile, with compliance of 85 per cent in Mecca, where a reservation application is already in use for certain areas, and 70 per cent in Kyoto, where such a system would be new. Information nudges provided real-time crowding information through applications and signage, with 55 per cent of agents in Mecca and 60 per cent in Kyoto receiving the information and responding according to their responsiveness parameter by delaying entry, altering routes or visiting alternative destinations. Route separation introduced one-way systems and separated inbound and outbound flows on the most congested links. Capacity capping held entrants to the highest-density zones below a threshold by queuing at entrances. Scenarios were run for representative peak days, with 30 replications each, and evaluated on peak density in the most crowded cells, mean waiting time, throughput measured as visitors completing their itineraries, and a satisfaction index on a 100-point scale derived from the survey-based crowding–satisfaction function.

4. Results

4.1 Baseline conditions

The calibrated baseline models reproduced the observed pattern of congestion at both destinations. In Mecca, peak densities in the Mataf and at the main gates reached 5.2 persons

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per square metre during the hour before Tarawih prayer, well above the threshold of about four persons per square metre at which movement becomes constrained, and mean waiting time at the gates exceeded 22 minutes. In Kyoto, peak densities in the Sannenzaka lane and at the Fushimi Inari torii gates reached 3.4 persons per square metre in the late morning, and the mean satisfaction index was 62, with survey respondents in the most crowded locations reporting satisfaction scores 25 points below those in uncrowded locations. These baselines confirmed the severity of congestion and provided the reference for scenario comparison.

4.2 Individual measures

Table 2 presents the results for each measure applied individually. Time-slot reservation produced the largest reduction in peak density at both destinations, 24 per cent in Mecca and 19 per cent in Kyoto, with reduced waiting times and a small increase in satisfaction, since flattening the arrival profile reduced crowding without preventing visits. Information nudges reduced peak density by 17 and 15 per cent respectively and raised satisfaction slightly, as agents who responded avoided the most crowded periods and locations while those who did not experienced somewhat less crowding. Route separation reduced peak density by 11 per cent in Mecca, where the geometry of the Masa'a and gate corridors allowed effective separation, but by only 6 per cent in Kyoto, where the narrow lanes offer few opportunities for separated flows and where one-way systems lengthened routes. Capacity capping reduced peak density by 26 per cent in Mecca and 22 per cent in Kyoto, comparable to reservation, but increased mean waiting time sharply and reduced satisfaction by seven and nine points, since visitors were held at entrances without knowing when they would be admitted. Throughput fell under capacity capping and route separation in Kyoto but was maintained under reservation and information.

Table 2: Scenario results for individual measures relative to baseline (mean of 30 replications)

Measure	Destination	Change in peak density (%)	Change in mean waiting time (%)	Change in throughput (%)	Satisfaction index (baseline Mecca 66, Kyoto 62)
Time-slot reservation	Mecca	−24	−31	+1	70
Time-slot reservation	Kyoto	−19	−27	0	66
Information nudges	Mecca	−17	−19	0	68
Information nudges	Kyoto	−15	−16	+1	65
Route separation	Mecca	−11	−8	+2	67
Route separation	Kyoto	−6	+4	−3	61
Capacity capping	Mecca	−26	+38	−5	59
Capacity capping	Kyoto	−22	+45	−7	53

Source: Authors' simulation results (2025)

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4.3 Combined measures

Table 3 presents the results for combinations. The combination of time-slot reservation and information nudges produced the largest reductions in peak density without loss of satisfaction, 34 per cent in Mecca and 29 per cent in Kyoto, with satisfaction within two points of, and in fact slightly above, the baseline. The two measures were complementary: reservation flattened the arrival profile while nudges redistributed visitors who arrived within their slots across locations and sub-periods. Adding route separation to this combination produced a further reduction of four percentage points in Mecca and one in Kyoto. Adding capacity capping produced the largest density reductions of all, 41 and 36 per cent, but at the cost of satisfaction declines of five and seven points, since the cap continued to bind at the highest peaks and generated queues. The combination of reservation and nudges therefore represents the most favourable trade-off at both destinations, with route separation a useful supplement where geometry permits.

Table 3: Scenario results for combined measures relative to baseline (mean of 30 replications)

Combination	Destination	Change in peak density (%)	Change in mean waiting time (%)	Satisfaction index (baseline Mecca 66, Kyoto 62)
Reservation + nudges	Mecca	−34	−42	72
Reservation + nudges	Kyoto	−29	−36	68
Reservation + nudges + route separation	Mecca	−38	−45	72
Reservation + nudges + route separation	Kyoto	−30	−34	67
Reservation + nudges + capacity capping	Mecca	−41	−12	61
Reservation + nudges + capacity capping	Kyoto	−36	−8	55
All four measures	Mecca	−43	−15	61
All four measures	Kyoto	−37	−9	54

Source: Authors' simulation results (2025)

4.4 Sensitivity to compliance and responsiveness

The effectiveness of reservation and nudges depends on compliance and responsiveness. Reducing reservation compliance from the assumed levels to 50 per cent reduced the density benefit of the combined scenario to 25 per cent in Mecca and 20 per cent in Kyoto, still exceeding any single physical measure. Reducing the proportion of agents receiving information to 30 per cent reduced the nudge contribution by roughly half. Conversely, raising compliance and reach to 90 and 80 per cent respectively increased the combined benefit to 40 and 35 per cent. These results indicate that the measures remain effective across realistic ranges but that investment in application adoption, communication and enforcement materially affects their value.

5. Discussion

5.1 Effective measures and their mechanisms

Measures acting on the timing and distribution of demand, reservation and nudges, outperform physical or restrictive measures when congestion and experience are both considered, consistent with Koens et al. (2018) on concentration and with the evidence on reservation reviewed by Manning (2011). Reservation reshapes the arrival profile before

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visitors arrive and depends on compliance, which is higher where it is framed as guaranteed access. Nudges act on visitors already present and depend on reach and on alternatives, which are greater in Kyoto, where visitors can substitute between sites, than in Mecca, where the object of the visit is singular. Capacity capping is effective for density but, as Gössling et al. (2019) note of restrictive measures, imposes costs that reservation and information avoid.

5.2 Transferability between destinations

The similarity of rankings across two very different destinations suggests that the core findings are transferable, with differences in magnitude and in the role of physical measures. Route separation was worthwhile in Mecca, where corridors are wide and flows structured by ritual, and marginal in Kyoto's narrow lanes. Regulatory capacity also differs: the Mecca precinct authority can require reservation and achieve high compliance, whereas Kyoto's authorities rely on voluntary adoption among many stakeholders. The pilgrim–tourist distinction of Collins-Kreiner (2010) is relevant: Mecca's visitors accept scheduling given its religious framing, whereas Kyoto's mixed visitors find choice-preserving information measures more acceptable.

5.3 A decision framework for sustainable pilgrimage tourism management

A decision framework follows. Managers should first characterise the temporal and spatial concentration of demand using counts and location data. Where arrival peaks dominate, reservation should be primary, framed as guaranteed access; where spatial concentration dominates and alternatives exist, nudges should be primary; in most cases the two should be combined. Physical measures should be assessed against site geometry and the acceptability of directed movement. Capacity capping should be reserved for safety thresholds and accompanied by reservation so that waiting is predictable. Consistent with Shinde (2021), the framework recognises that religious authorities and tourism agencies weigh satisfaction, safety and spiritual quality differently, and calibrated agent-based models can serve as a shared tool for negotiating these trade-offs before measures are imposed on visitors.

6. Conclusion

This paper applied agent-based visitor flow modelling to the Grand Mosque precinct in Mecca and the eastern pilgrimage corridors of Kyoto and evaluated four management measures. Scenario analysis identified time-slot reservation and information nudges as the most effective measures for reducing congestion without lowering satisfaction, with the combination reducing peak densities by 34 per cent in Mecca and 29 per cent in Kyoto while maintaining satisfaction. Capacity capping achieved comparable density reductions at a significant cost to satisfaction, and route separation was useful in Mecca but marginal in Kyoto. The consistency of findings across the two destinations supports transferability, while differences in magnitude highlight site geometry and regulatory capacity. A decision framework was proposed to guide selection of measures at sacred sites.

The study has limitations. The models represent visitor behaviour through rules estimated from surveys and observations and cannot capture all the ways in which people respond to management measures; compliance and responsiveness assumptions, though tested through sensitivity analysis, remain uncertain until measures are implemented. The satisfaction index is derived from stated relationships between crowding and experience and does not capture the spiritual dimensions of pilgrimage that may be affected by scheduling. Calibration relied on data for particular peak periods in 2025 and may not reflect other seasons or future growth. Future research should validate the model predictions against the observed effects of measures as they are implemented, extend the approach to other pilgrimage destinations

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including Varanasi, Lourdes and Santiago de Compostela, incorporate resident impacts alongside visitor outcomes, and examine how reservation and information systems can be designed to respect the religious meaning of pilgrimage while managing its scale.

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References

Bonabeau, E. (2002). *Agent-based modeling: Methods and techniques for simulating human systems.* Proceedings of the National Academy of Sciences, 99(suppl. 3), 7280–7287. https://doi.org/10.1073/pnas.082080899

Collins-Kreiner, N. (2010). Researching pilgrimage: Continuity and transformations. *Annals of Tourism Research, 37*(2), 440–456. https://doi.org/10.1016/j.annals.2009.10.016

Fruin, J. J. (1971). *Pedestrian planning and design.* Metropolitan Association of Urban Designers and Environmental Planners.

Gössling, S., Scott, D., & Hall, C. M. (2019). Global trends in length of stay: Implications for destination management and climate change. *Journal of Sustainable Tourism, 27*(12), 1930–1949.

Helbing, D., Johansson, A., & Al-Abideen, H. Z. (2007). Dynamics of crowd disasters: An empirical study. *Physical Review E, 75*(4), 046109. https://doi.org/10.1103/PhysRevE.75.046109

Helbing, D., & Molnár, P. (1995). Social force model for pedestrian dynamics. *Physical Review E, 51*(5), 4282–4286. https://doi.org/10.1103/PhysRevE.51.4282

Itami, R., Raulings, R., MacLaren, G., Hirst, K., Gimblett, R., Zanon, D., & Chladek, P. (2003). RBSim 2: Simulating the complex interactions between human movement and the outdoor recreation environment. *Journal for Nature Conservation, 11*(4), 278–286. https://doi.org/10.1078/1617-1381-00058

Koens, K., Postma, A., & Papp, B. (2018). Is overtourism overused? Understanding the impact of tourism in a city context. *Sustainability, 10*(12), 4384. https://doi.org/10.3390/su10124384

Manning, R. E. (2011). *Studies in outdoor recreation: Search and research for satisfaction (3rd ed.).* Oregon State University Press.

Nagai, H. (2021). Overtourism in Kyoto: Residents' perceptions and municipal responses. *Journal of Tourism Studies, 33*(1), 45–61.

Shinde, K. A. (2021). *Sustainable pilgrimage tourism: Challenges and opportunities.* In D. J. Timothy & D. H. Olsen (Eds.), Routledge handbook of religious and spiritual tourism (pp. 305–318). Routledge.

Thaler, R. H., & Sunstein, C. R. (2008). *Nudge: Improving decisions about health, wealth, and happiness.* Yale University Press.

Zheng, W., Huang, X., & Li, Y. (2017). Understanding the tourist mobility using GPS: Where is the next place? *Tourism Management, 59*, 267–280. https://doi.org/10.1016/j.tourman.2016.08.009

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