

HIGH CROWD DENSITY MEASUREMENTS FROM RAMADAN AT MAKKAH, 2025

ANDERS JOHANSSON^{a,*}, CAMERON DOBBIE^a, KHALED ALBOSTAH^b,
RAINALD LÖHNER^c, JÜRGEN BRADATSCH^b, KNUT HAASE^d,
YARA ALSHALHOUB^e, SALIM AL-BOSTA^e

^a University of Bristol, School of Engineering Mathematics and Technology, Bristol BS8 1TW, United Kingdom

^b SL Rasch GmbH, Paracelsusstraße 26, 70599 Stuttgart, Germany

^c Center for Computational Fluid Dynamics, George Mason University, Fairfax, VA, USA

^d University of Hamburg Business School, Mittelweg 177, 20148 Hamburg, Germany

^e Royal Commission for Makkah City and Holy Sites, Makkah, Kingdom of Saudi Arabia

* corresponding author: a.johansson@bristol.ac.uk

ABSTRACT. We provide an extensive set of measurement data from Ramadan 2025 at Makkah, Kingdom of Saudi Arabia. Our data covers a wide set of locations around the Holy Mosque (Al Haram). Unlike previous studies of pilgrim flow in Makkah, we analyse the pilgrim behaviour over a large area and over a long period of time, which reveals interesting patterns over space and time.

Our dataset covers crowd movement in the high density, multi-cultural, multi-age, multi-fitness regime. This data is needed to better understand the movement and the behaviour of high density crowds in order to safely manage such crowds.

Analysing real, empirical, crowd flow as opposed to controlled experiments give rise to a number of challenges which are discussed in our paper.

KEYWORDS: Empirical crowd analysis, Ramadan pilgrim behaviour analysis, computer vision.

1. INTRODUCTION

Makkah is a city in the Kingdom of Saudi Arabia, which is welcoming millions of pilgrims to the Hajj and the Umrah pilgrimages. A particularly crowded period is during the month of Ramadan. Makkah has been studied extensively, but previous crowd studies in Makkah have focused mainly on:

- The Hajj (main pilgrimage), or
- Extreme density hot-spots such as Jamarat [1] and Al Haram [2–4].

This study analyses a somewhat different dataset, based on ten cameras installed in key locations on the main routes into and out of Al Haram (the Holy Mosque). These cameras recorded video for 24 hours per day, during a 7-day period in the last week of Ramadan in 2025. See Figure 1 for the specific locations of the cameras.

A particular area of interest is to produce a fundamental diagram (i.e. the speed-density relationship), which can be used for design and crowd management in Makkah.

There have been many previous studies on the fundamental diagram for pedestrians [5–10], some of them capturing high density crowds [1, 2, 11–13]. Furthermore, different theories and fit functions have been proposed [14–17].

Specifically, a proliferation of ‘smart systems’ to collect data on crowd movement have been deployed in and around Makkah over the past 20 years [18–20].

Numerous studies have also been conducted to model the behavior of the crowds during Hajj and Umrah [21].

2. MATERIALS AND METHODS

2.1. DATASET

The locations of the ten cameras used in this study are shown in Figure 1. Note that the cameras are located *around* the Holy Mosque (Al Haram), to capture the movement and patterns of the crowds going into and out of the area around the mosque. However, unlike other studies, the cameras are not located inside the mosque itself (where the crowd density is known to be extremely high). The benefit of these camera placements, is to collect a broader set of insights into crowd behaviour over the course of a week, in order to capture the daily peaks and troughs, and the range of crowd conditions over the course of a week (as opposed to analysing a small snapshot of time within a confined area).

2.2. METHOD

Each of the ten cameras is processed using a proprietary Computer Vision algorithm trained specifically on Makkah specific data, in order to accurately detect and track each pedestrian, for different levels of crowd density. Note that most off-the-shelf pedestrian models work well for low crowd density, but they tend to break down at high density, which is why adaptations

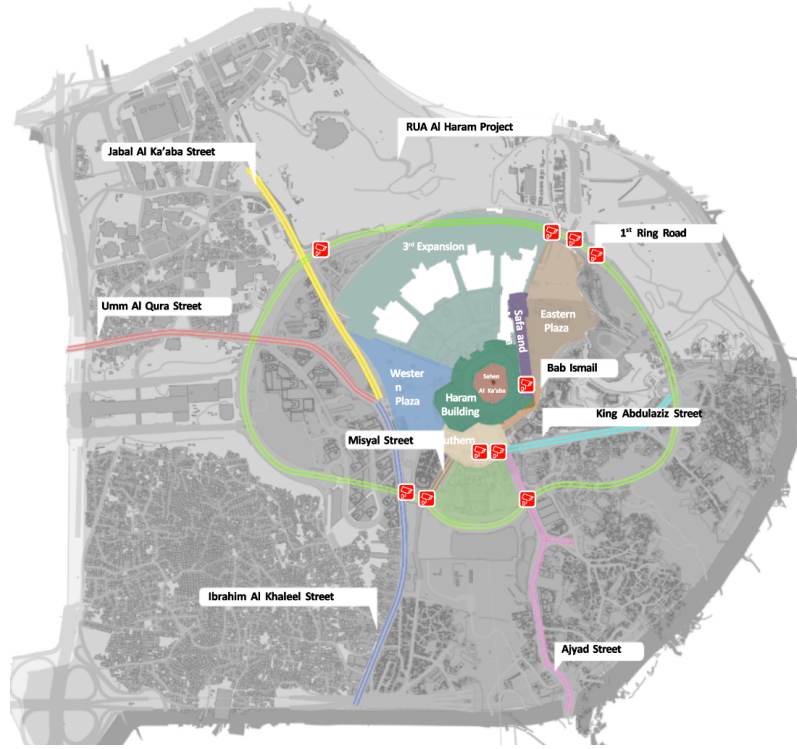


FIGURE 1. Locations of cameras used in this study (red markers). Note that most cameras are located around the 1st ring road of Makkah, and therefore cover the main flows into and out of Al Haram (the Holy Mosque).

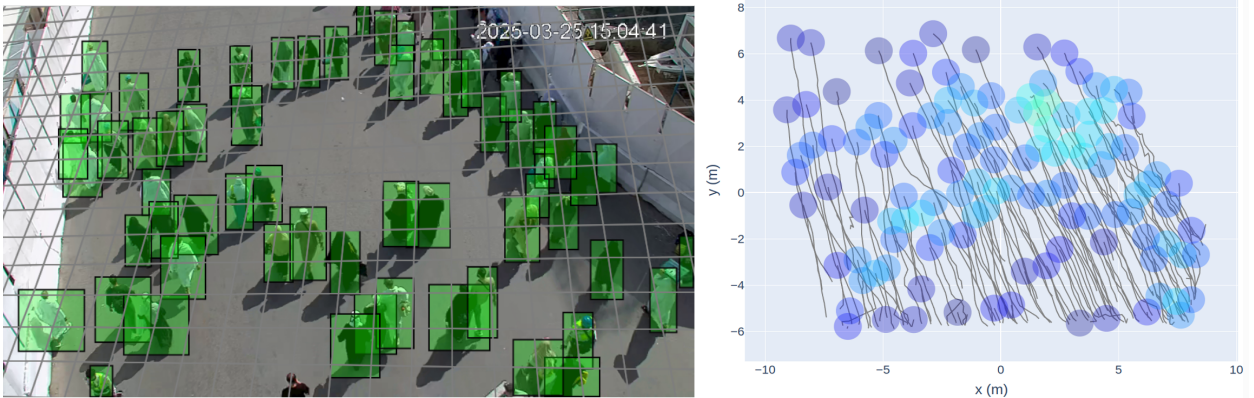


FIGURE 2. Left: Example of pedestrian detections from video (the lattice is a $1\text{ m} \times 1\text{ m}$ grid). Right: Example of pedestrian trajectories extracted from video.

are required in order to collect accurate data over the whole density spectrum. See Figure 2 for an example output.

Since we are interested in accurate measurements of crowd density (m^{-2}) and flow ($\text{m}^{-1}\text{s}^{-1}$), as opposed to just people counts, we need to carefully calibrate each camera in order to be able to translate positions in pixels and walking speeds in pixels per second, to SI units (International System of Units) of positions in metres, and walking speeds in metres per second.

In order to do this calibration, the dimension in metres of known objects on the ground (such as floor tiles, height of fences and street widths) were measured. Then an optimisation model was used to find the best camera parameters to match the camera measurements with the known reference objects on the ground.

Specifically, the Trust Region Reflective (TRF) optimisation method is used to find the camera parameters that best fit the ground truth parameters. The camera parameters that are optimised are the camera's pitch, roll, yaw, field-of-view, and height above the ground plane.

This optimisation process gives a spatial accuracy of $a = 98\%$ which is in the same region as the measurement tolerance of the reference objects. This means that for crowd density, the accuracy will be $a^2 = 96\%$.

Once the camera has been calibrated, we can map each pixel position (u, v) , onto a corresponding real-world Cartesian coordinate system in metres $\vec{x}$. For an individual pedestrian who has been tracked from $\vec{x}(t)$ to $\vec{x}(t + \Delta t)$, their walking velocity can be calculated

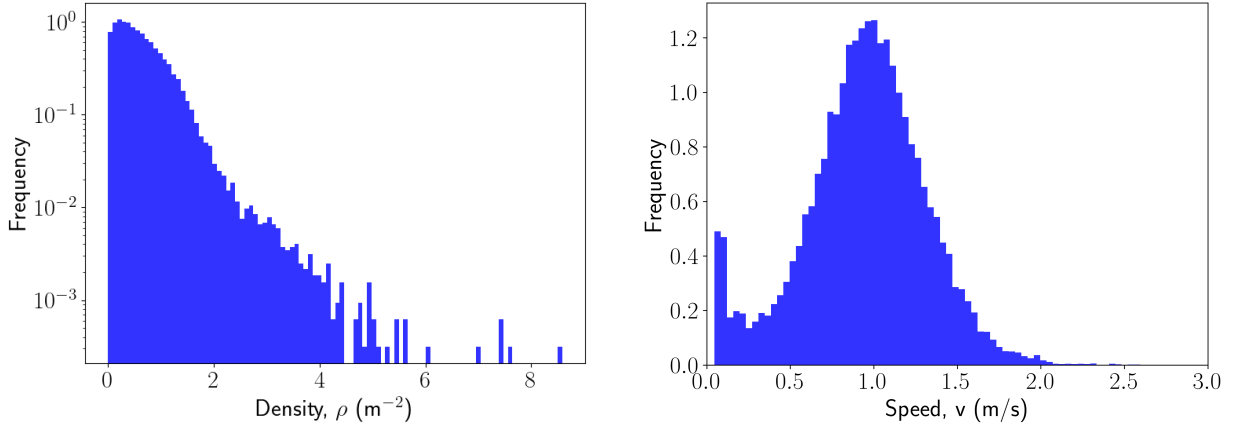


FIGURE 3. Left: Distribution of crowd density. Note that the distribution is heavily concentrated on density values up to 4 m^{-2} , and therefore a logarithmic scale is used in order for higher density data points to be visible. Right: Distribution of free walking speeds (for crowd densities $\leq 0.5 \text{ m}^{-2}$).

as:

$$\vec{v} = \frac{\vec{x}(t + \Delta t) - \vec{x}(t)}{\Delta t}. \quad (1)$$

2.3. DENSITY

In order to measure crowd density, we use the Voronoi method, whereby a Voronoi diagram [22] is calculated based on all positions of pedestrians in the field of view, and the density around each pedestrian is then calculated as the inverse of the cell area around that pedestrian.

Note that, in order to maintain data integrity, we exclude all truncated Voronoi cells (at the outer boundary) from any further analysis.

See Figure 3 for the density distribution. Note that even though density values over 4 m^{-2} are occasionally measured, the vast majority of values are below 4 m^{-2} .

2.4. WALKING SPEED

Unlike for controlled experiments [8], we have to be careful not to assume that every detected pedestrian has an intent to purposefully walk at their ‘free’ walking speed in order to reach a destination. Indeed, even though a large part of the detected pedestrians are part of the ‘main flow’ (i.e. either walking towards Al Haram, or leaving it), there are also numerous pilgrims who dwell under the cameras for various reasons (e.g. to rest, to pray, or to wait for their group members). Looking at the distribution of ‘free’ walking speeds (i.e. speeds for crowd densities $< 0.5 \text{ m}^{-2}$) in Figure 3, the following observations are made: (i) the average walking speed is somewhat lower than walking speeds measured in other studies, and (ii) there is a higher than expected number of pedestrians at very low speeds.

The reason for the small peak at low speeds is the ‘dwelling’ issue mentioned above. The reasons for the average speed being slightly lower than that measured in other studies are as follows:

- Age: The demographic is older than the average for most other studies.
- Temperature: The ambient temperature is higher than in most other studies [23, 24].
- Long walking distances: Pilgrims walk for long distances which means that fatigue will impact on walking speed.

All of these factors are known to contribute to a drop in walking speed [14].

3. RESULTS

3.1. FUNDAMENTAL DIAGRAM

Since pedestrians sometimes stop to pray under the cameras (i.e. a period of time with high crowd density and almost zero walking speed), we filter out time periods during the known prayer times from our datasets before we generate fundamental diagrams. Furthermore, we also filter out any pedestrian that has been in the field of view of a single camera for over 60 seconds, as that would likely indicate a ‘dwelling’ pedestrian.

Figure 4 shows the median speed (and flow) as a function of crowd density, within 0.25 m^{-2} density buckets.

A Weidmann curve is used to fit the data [14]:

$$v_{fit}(\rho) = \max \left[0.081, 0.99 \left(1 - e^{-4.53 \left(\frac{1}{\rho} - \frac{1}{4.95} \right)} \right) \right]. \quad (2)$$

The nature of the lower bound (0.081 m s^{-1}) is analysed and discussed in [15].

3.2. FLOW PROFILE

In the previous section, we analysed the flow-density relationship in our data, which is a useful construct in order to generalise the crowd dynamics and to ensure that enough road capacity is provided.

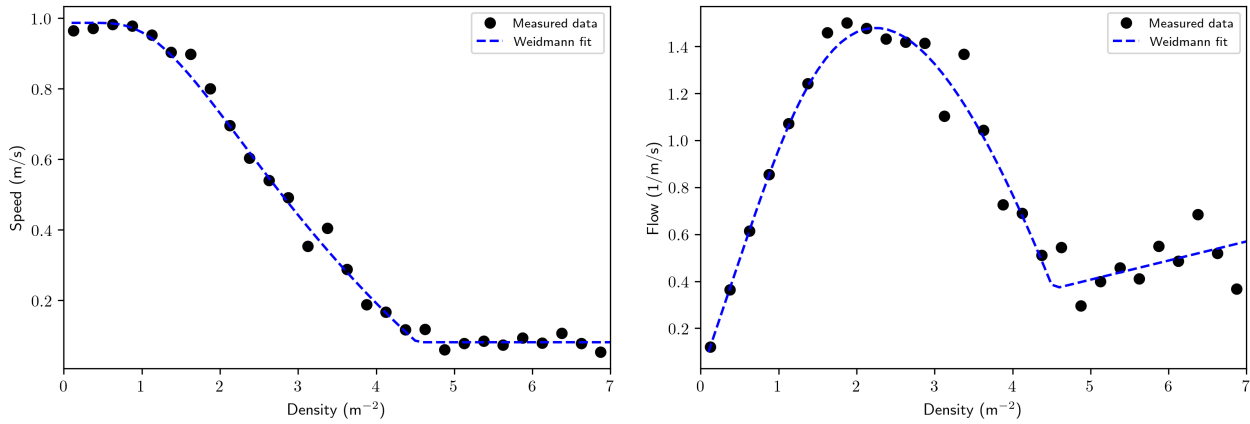


FIGURE 4. Left: Density vs speed. Right: Density vs flow. Empirical data (black dots), with a Weidmann fit function (dashed blue line).

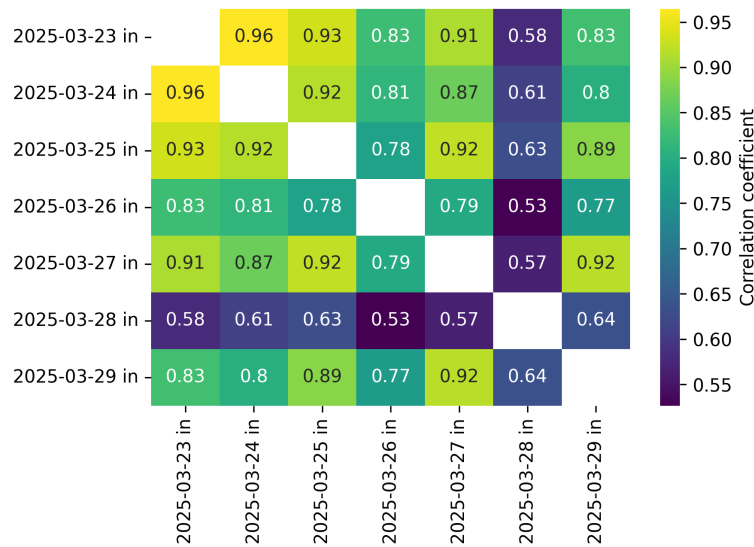


FIGURE 5. Pearson correlation coefficient for each of the days vs each of the other days during the week.

In order to gain further insights into specific crowd behaviours in our dataset, we will now shift our attention to analysing the flow as a function of time.

Since our cameras cover a large area surrounding Al Haram, we estimate that we cover approximately 40 % of all flow into and out of Haram. We can therefore measure the flow under each camera and add them together, in order to create a representative flow profile over time (i.e. the demand function).

There is a strong correlation from one day to the next. In order to quantify this, we use the Pearson correlation coefficient to measure the correlation r in flow between pairs of days over the week – see Figure 5. For most pairs of days, there are strong correlations. However, there is one exception, which is the 28th of March 2025, which is a Friday and therefore a special day in Islam, with a known difference in behaviour compared to other days.

Figure 6 shows the in-flow (positive values) and out-flow (negative values) for each day. The following observations can be made:

- (1) There is a striking repeating pattern for each day (except Friday the 28th of March).
- (2) The dashed lines show the time of each prayer. There is a clear ingress peak (positive flow) before each prayer, and a corresponding egress peak (negative flow) just after the prayer.
- (3) The profiles of the ingress and egress peaks are somewhat different, where the egress flow is more concentrated within a small period of time, compared to the ingress flow which is flatter and spread out over a longer period of time.
- (4) The peaks of the ingress curves usually occur in the afternoon/evening (before Asr and Maghrib), whereas the peaks in egress usually occur the following morning (after Tahajjud and Fajr). This suggests that many people enter the area for the evening prayers and stay until after the morning prayers before leaving again.

For crowd management purposes, it is important to be able to quantify when and how the highest load

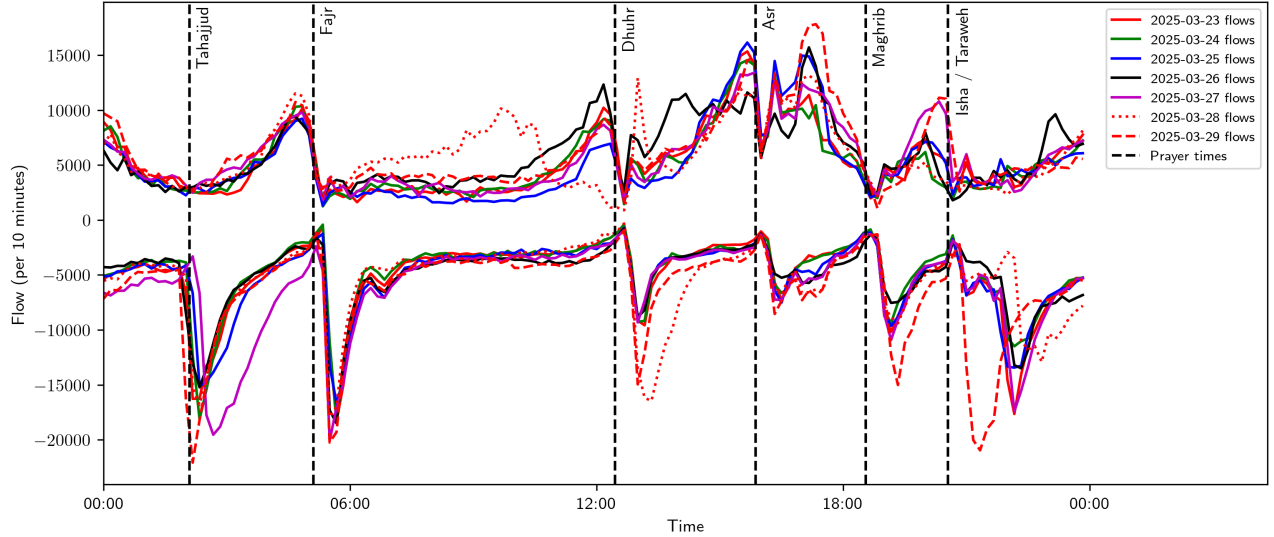


FIGURE 6. Time series of flow into Haram (positive values) and out of Haram (negative values). Note that the Tahajjud prayer, while occurring in the early hours of the morning, is considered the last prayer of the previous day.

Date	Fajr	Dhuhr	Asr	Maghrib	Isha	Taraweh	Tahajjud
2025-03-23	31.5 %	31.8 %	26.2 %	25.4 %	33.5 %	25.4 %	28.0 %
2025-03-24	34.0 %	33.8 %	25.6 %	27.3 %	28.9 %	21.8 %	23.6 %
2025-03-25	29.9 %	31.0 %	24.6 %	25.9 %	29.4 %	23.2 %	25.2 %
2025-03-26	33.5 %	31.8 %	19.4 %	22.3 %	34.4 %	23.6 %	24.6 %
2025-03-27	30.1 %	31.2 %	22.2 %	26.6 %	34.5 %	25.6 %	26.8 %
2025-03-28	34.9 %	25.1 %	20.1 %	24.7 %	21.2 %	22.3 %	27.8 %
2025-03-29	33.6 %	33.5 %	21.0 %	28.1 %	24.7 %	—	—

TABLE 1. Ramadan prayer egress analysis showing the percentage of egress flow that occurs within the 15-minute peak of the egress profile. Larger values denote prayers where the egress flow is particularly concentrated at the peak. Note that Tahajjud takes place in the early hours of the following day for any given date. Taraweh and Tahajjud do not occur on the final night of Ramadan.

on the infrastructure occurs. It is clear from our flow profiles that the maximum crowd flow occurs during the egress following each prayer.

Fruin [16] analysed 60-minute egress flow and measured the percentage of the volume of that flow that occurred during the 15 minutes peak flow. He came to an average value of 40 % of the egress flow occurring within the peak, which is a useful approximation to use for crowd management and design.

In order to use Fruin’s methodology, we apply this for each day, and each prayer in Table 1. The results show a range of values, somewhat lower than 40 % (closer to 30 %).

4. CONCLUSIONS

We have presented the analysis of a unique dataset, collected continuously for 24-hours per day over a whole week, at the end of the month of Ramadan. We highlighted some issues that need to be taken into account (e.g. filtering out ‘dwelling’ pedestrians) in order to analyse empirically observed crowd flow, as opposed to crowd flow during controlled experimental conditions.

Furthermore, we presented analysis of flow patterns

which revealed repeating patterns, governed mostly by the pre-set prayer times; and we provided some insights that are useful in order to manage crowds during the month of Ramadan, such as predicting when the main peaks will occur.

Previous fundamental diagrams obtained in Makkah, have focused on the most extreme density hot-spots; such as inside the Holy Mosque (Al Haram) [2] and at the Jamarat bridge [1]. Our results are from streets surrounding the Holy Mosque (as opposed to inside the mosque itself). Therefore, the motivation and behaviour of the crowd will inevitably be different. In our dataset, even though we have seen some localised high-density occurrences, we have not observed sustained high density at the sort of levels that have been observed in the previous studies mentioned above. Furthermore, we have not observed stop-and-go waves or turbulent motion.

Future work will seek to unify the various different fundamental diagrams, and to analyse their differences and similarities.

Even though we provided insights into some of the challenges (and related solutions) when trying to gen-

eralise from empirical observations of crowds 'in the wild', we will expand on this in future work with the aim of providing a comprehensive methodology of how to analyse empirical crowds 'in the wild' (which is significantly different from analysing controlled experiments).

REFERENCES

- [1] D. Helbing, A. Johansson, H. Z. Al-Abideen. Dynamics of crowd disasters: An empirical study. *Physical Review E* **75**:046109, 2007. <https://doi.org/10.1103/PhysRevE.75.046109>
- [2] R. Löhner, B. Muhamad, P. Dambalmath, E. Haug. Fundamental diagrams for specific very high density crowds. *Collective Dynamics* **2**:1–15, 2018. <https://doi.org/10.17815/CD.2017.13>
- [3] A. M. Aljohani. *Pilgrim crowd dynamics*. Ph.D. thesis, University of Birmingham, 2015.
- [4] W. S. Halabi. *Overcrowding and the Holy Mosque, Makkah, Saudi Arabia*. Ph.D. thesis, Newcastle University, 2006.
- [5] W. M. Predtetschenski, A. I. Milinski. *Personenströme in Gebäuden: Berechnungsmethoden für die Projektierung [In German; Pedestrian Flow in Buildings: Calculation Methods for Design]*. Verlagsgesellschaft Rudolf Müller, Köln-Braunsfeld, 1971.
- [6] L. D. Vanumu, K. Ramachandra Rao, G. Tiwari. Fundamental diagrams of pedestrian flow characteristics: A review. *European transport research review* **9**(4):49, 2017. <https://doi.org/10.1007/s12544-017-0264-6>
- [7] U. Chattaray, A. Seyfried, P. Chakroborty. Comparison of pedestrian fundamental diagram across cultures. *Advances in Complex Systems* **12**(03):393–405, 2009. <https://doi.org/10.1142/S0219525909002209>
- [8] A. Seyfried, B. Steffen, W. Klingsch, M. Boltes. The fundamental diagram of pedestrian movement revisited. *Journal of Statistical Mechanics: Theory and Experiment* **2005**(10):P10002, 2005. <https://doi.org/10.1088/1742-5468/2005/10/P10002>
- [9] A. Jelić, C. Appert-Rolland, S. Lemercier, J. Pettré. Properties of pedestrians walking in line: Fundamental diagrams. *Physical Review E* **85**:036111, 2012. <https://doi.org/10.1103/PhysRevE.85.036111>
- [10] E. Bosina. *A New Generic Approach to the Pedestrian Fundamental Diagram*. Ph.D. thesis, ETH Zürich, 2018. <https://doi.org/10.3929/ethz-b-000296226>
- [11] M. Mōri, H. Tsukaguchi. A new method for evaluation of level of service in pedestrian facilities. *Transportation Research Part A: General* **21**(3):223–234, 1987. [https://doi.org/10.1016/0191-2607\(87\)90016-1](https://doi.org/10.1016/0191-2607(87)90016-1)
- [12] A. Polus, J. L. Schofer, A. Ushpiz. Pedestrian flow and level of service. *Journal of Transportation and Pipeline Engineering* **109**(1):46–56, 1983.
- [13] T. Kretz. An overview of fundamental diagrams of pedestrian dynamics, 2019. Preprint. <https://doi.org/10.13140/RG.2.2.30070.96326>
- [14] U. Weidmann. *Transporttechnik der Fussgänger – Transporttechnische Eigenschaften des Fussgängerverkehrs, Literaturlauswertung [In German; Pedestrian transport technology – transport-technical properties of pedestrian traffic, literature review]*. Literature research, Institut für Verkehrsplanung, Transporttechnik, Strassen- und Eisenbahnbau IVT an der ETH Zürich, 1993. <https://doi.org/10.3929/ethz-b-000242008>
- [15] A. Johansson. Constant-net-time headway as a key mechanism behind pedestrian flow dynamics. *Physical Review E* **80**:026120, 2009. <https://doi.org/10.1103/PhysRevE.80.026120>
- [16] J. J. Fruin. *Designing for pedestrians a level of service concept*. Polytechnic University, 1970.
- [17] J. J. Fruin. *The Causes and Prevention of Crowd Disasters*. Crowd Safety, 2002.
- [18] E. A. Felemban, F. U. Rehman, S. A. A. Biabani, et al. Digital revolution for Hajj crowd management: A technology survey. *IEEE Access* **8**:208583–208609, 2020. <https://doi.org/10.1109/ACCESS.2020.3037396>
- [19] A. N Alhawsawi, A. Ahmad, F. U. R. Rehman, et al. Surveying challenges for enhancing precision in Hajj crowd simulation, 2020. Preprint.
- [20] A. M. Al-Shaery, S. G. Ahmed, H. Aljassmi, et al. Open dataset for predicting pilgrim activities for crowd management during Hajj using wearable sensors. *IEEE Access* **12**:72828–72846, 2024. <https://doi.org/10.1109/ACCESS.2024.3402230>
- [21] A. Owaidah, D. Olaru, M. Bennamoun, et al. Review of modelling and simulating crowds at mass gathering events: Hajj as a case study. *Journal of Artificial Societies and Social Simulation* **22**(2):9, 2019. <https://doi.org/10.18564/jasss.3997>
- [22] B. Steffen, A. Seyfried. Methods for measuring pedestrian density, flow, speed and direction with minimal scatter. *Physica A: Statistical mechanics and its applications* **389**(9):1902–1910, 2010. <https://doi.org/10.1016/j.physa.2009.12.015>
- [23] S. P. Obuchi, H. Kawai, J. C. Garbalosa, et al. Walking is regulated by environmental temperature. *Scientific Reports* **11**(1):12136, 2021. <https://doi.org/10.1038/s41598-021-91633-1>
- [24] S. M. Al-Bosta, A. Johansson, Y. K. Al-Shalhoub. The effect of hot weather on the characteristics of crowd movement in the holy sites during the hajj season. In *The 24th Scientific Forum for Hajj, Umrah and Madinah Visit Research*, p. 33. 2024.