Designing a Large-Scale Crowd Management System

By: Jill O'Keefe

Introduction

The Hajj, the annual Islamic pilgrimage to Mecca, is the largest pedestrian gathering in the world. Anytime large numbers of people gather, there is always a risk of injury and death due to stampedes. Several deadly incidents have occurred over the years. In 2006, 364 pilgrims were killed when they tripped over luggage and were crushed by the massive crowd at the Jamarat Bridge, the location where pilgrims perform the stoning-of-the-devil ritual.

After this deadly episode, the Ministry of Municipal and Rural Affairs (MOMRA) in Saudi Arabia undertook a project to improve the safety of the annual pilgrimage. Understanding that the Hajj is one of the five pillars of the Islamic faith, and knowing that the number of Muslims in the world is growing, Saudi Arabia wanted to improve the experience for increasing numbers of pilgrims each year.

The initial assessment cited problems with crowd management, circulation, and infrastructure. During peak times, huge crowds overflowed the religious sites, causing a dangerous environment. Especially dangerous were locations where streams of pilgrims were intersecting each other or flowing in opposite directions. In addition, public transportation to and from the religious sites from the enormous tent cities were over-burdened and were not keeping up with demand.

Forecasting Hajj Participation

Because the Hajj is such an enormous event, accurate planning is crucial to make sure there is enough infrastructure to support the number of pilgrims in attendance. Everything from tents and food to transportation and medical personnel depend on these forecasts. Luckily, the Hajj is an annual event and there is plenty of past data to use for this forecast.

This case study is focuses primarily on the crowd movements during the week. In order to forecast the number of pilgrims traveling along roads, through a religious site, or back to the tent city, previous data will be needed. An ARIMA or Exponential Smoothing Model would be able to determine not only the changes within a week, but also the trends between years.

Given
-Previous pilgrim density/movement data for the road network throughout the Hajj week using short time intervals. -Previous religious site entrance/exit time data by Hajj day and time. -Previous public transportation utilization data and queue length by Hajj date day and time.
Use
ARIMA or Exponential Smoothing Model
To
Determine the pilgrim traffic forecasts on the roads, religious sites, and public transportation throughout the Hajj week for the upcoming year.

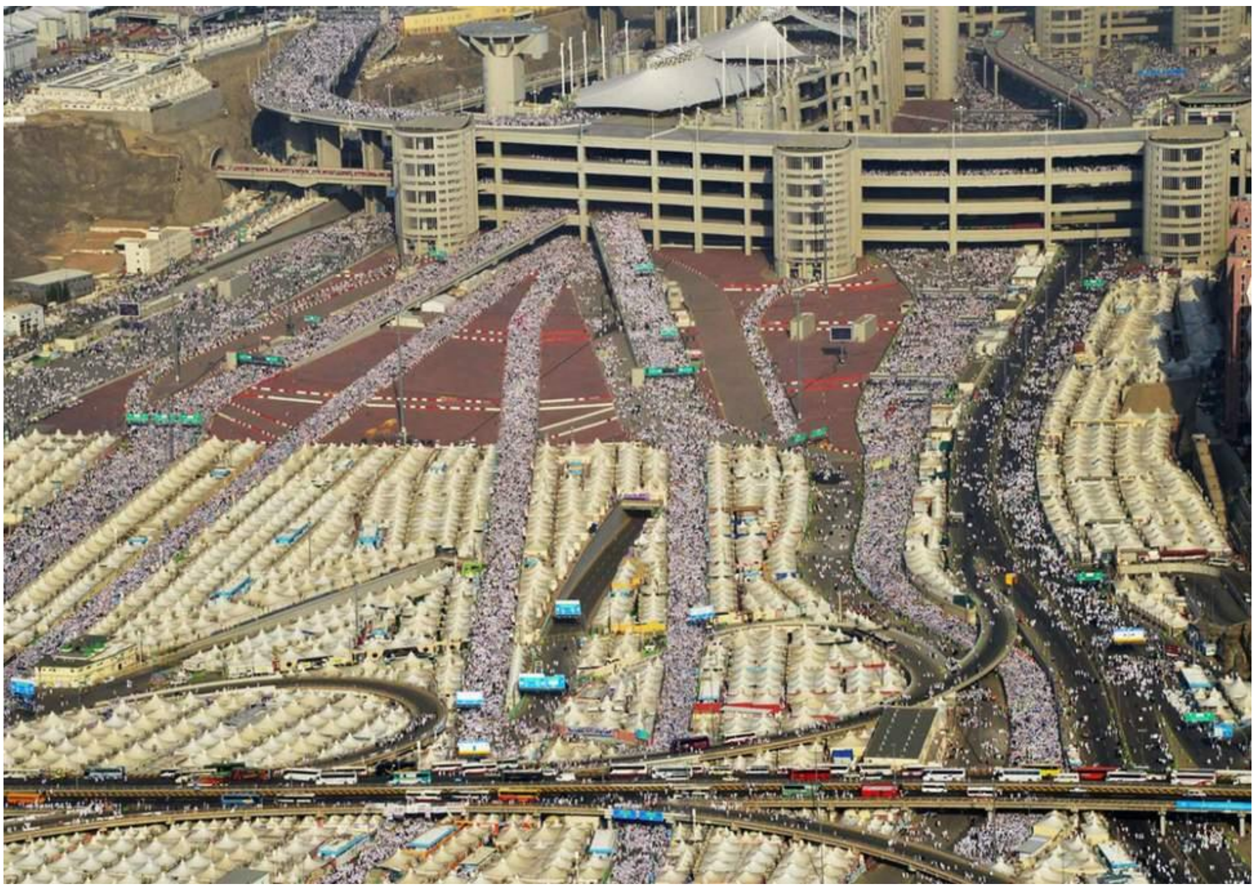
The forecasted pilgrim volume throughout the Mecca region over the duration of the Hajj can be used to stage security personnel and plan traffic flow in order to help the pilgrims reach their destinations safely and smoothly. These forecasts will be used in the following sections to prepare the city for the annual influx of pilgrims.

Maximum Safe Capacity of the Jamarat Bridge in Mina

The tragedy at the Jamarat Bridge highlighted problems with safety and traffic flow at the site. A simulation model of the site could be used to determine the appropriate entry rate. A Poisson distribution can be used to model the arrivals. In this case, the resources are the three pillars that are stoned by the pilgrims. In order to maintain a safe environment, the simulation will need to determine the maximum entry rate allowable to prevent a long queue from forming within the site.

Given
-The capacity of the network of roads and ramps leading to the Jamarat Bridge Complex -The exponential distribution of time pilgrims stay at the stoning site from previous years' data -The hours/days that pilgrims are allowed to enter the site
Use
Simulation of the Jamarat Bridge Complex
To
Determine the maximum number of pilgrims per unit of time that can visit the site

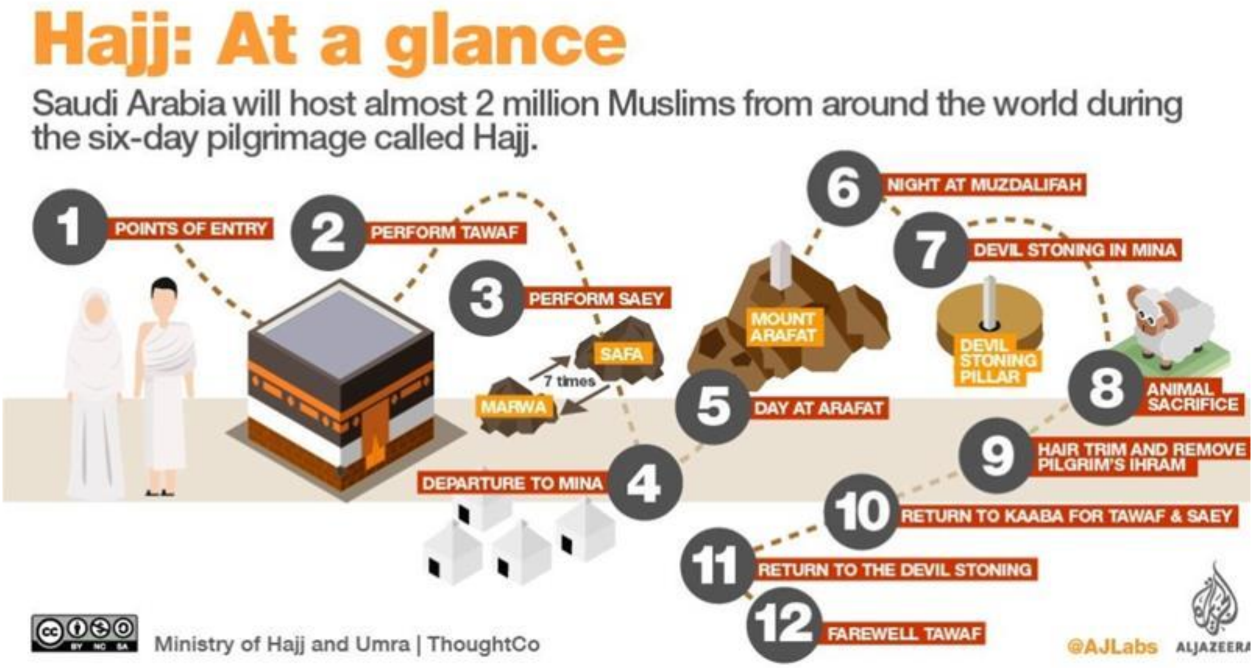
I believe that after simulating the Jamarat Bridge complex, the Saudi government discovered that the complex just didn't have the capacity to safely accommodate the increasing number of pilgrims. Following the 2006 tragedy, the old Jamarat Bridge was demolished and a new bridge was built. The new bridge has four levels: a ground level and three upper levels. The previous bridge had only two levels. In addition to these two new levels, individual ramps to each of the levels were added to keep the pedestrian traffic flowing in one direction. The new bridge also includes emergency exit ramps.



In order to smooth out the demand, each sector of tents was assigned a time for stoning. Strict control of the timing prevents surges at the site and improves the experience for the pilgrims.

Transportation Between Holy Sites

Pilgrims attending the Hajj travel between holy sites in a traditional manner. The following diagram shows the circulation of the pilgrims. Because many of these sites are far from each other, dedicated metro cars and buses are provided to transport the pilgrims across the area. The Saudi government has also implemented a "time ticket" system for the transportation to prevent surges and to keep the pilgrims circulating.



Previously, the Saudi government encountered additional problems once the pilgrims were off the public transportation and moving through the city. The sheer volumes of people moving to and from the sites created pedestrian traffic jams that could lead to injuries in the case of a stampede. The goal was to control the flow of people to provide enough space for the pilgrims to move to and from the sites while avoiding intersecting and two-way traffic.

This situation could be remedied with a mixed-integer optimization algorithm. In this case, the road layout can be modeled with a network flow model. Each street can be assigned as one way in one direction, one way in the other direction, or closed. The weights of the roads would be their capacity, which would be proportional to their width. The connected network must be able to supply enough street space for the pilgrims to circulate in a moderately-dense, but safe manner. The optimization problem can be defined as follows:

Given
-The network of streets in the city and their capacities
-The number of pilgrims at a given time moving from one holy site to another determined by the forecasting step
-The speed of the pilgrims through the streets
-No intersecting or two-way flows
Use
Mixed integer network optimization
To
Determine the optimal one-way road circulation network

This optimal network will change from day to day depending on the sites that the pilgrims are visiting. In addition, conditions on the road can change over time. Because some of the pilgrims walk from site to site while others ride public transportation, surges can still occur. Mecca and the surrounding areas have been equipped with radio-frequency and video technologies that monitor the circulation of the pilgrims. This provides an opportunity to use another analytics model to address real-time traffic problems.

Given
-The current road flow assignment -The maximum safe pilgrim density on each street -The available unused streets -Real-time traffic density measurements
Use
Change Detection
To
Determine when roads surpass a critical density value in order to deploy security forces to manage crowds and open overflow streets.

This change detection model will track the density of the pedestrians in real-time. The model will be fine-tuned so that random fluctuations within safe limits or a temporary moderate surge will not trigger a reaction. When the pilgrim density has surpassed a critical level for a given amount of time or a spike in density occurs, the system will be triggered and security personnel will deploy to the trouble spot to determine the cause of the congestion.

If the congestion is caused by a security issue, the police will resolve the issue as quickly as possible, rerouting the traffic, if necessary. If there is simply a congestion issue due to a heightened number of pilgrims on the road, the police will open an adjacent street and relieve the congestion. This modification can be rescinded once the congestion falls below a minimum trigger level.

Conclusion

Since the Saudi government implemented these changes in 2007, no crowd disasters have occurred, even with the number of pilgrims increasing each year. Furthermore, by targeting the security personnel on places with higher congestion, the government has been able to save 20% on personnel costs.

The success of Saudi Arabia’s crowd-management system can be used as a model for other cities experiencing large crowd movements. By keeping the pedestrians moving in one direction and dynamically modifying the routes when needs arise, the overall safety of the crowd is maintained.

Because this system is scalable, the security forces during the Hajj should be able to provide a positive pilgrimage experience for years to come.

References

"A Step-by-step Guide to Hajj," *Al Jazeera*, 30 August 2017, www.aljazeera.com/focus/hajj/2009/11/2009111895127111168.html.

"Using Analytics to Safely Manage Large-Scale Crowds." *Informs*, www.informs.org/Impact/O.R.-Analytics-Success-Stories/Using-Analytics-to-Safely-Manage-Large-Scale-Crowds. Accessed 11 April 2019.