Analyzing Pedestrian Movement in Mataf Using GPS and GIS to Support Space Redesign

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Key words: Pedestrian movement analysis, GPS, GIS, Hajj, Makkah, Tawaf

Abstract: Evaluating the use of architectural and urban spaces is an important issue for architects and urban designers who wish to enhance space usability. Space usability is crucial in crowded spaces such as Mataf areas. Millions of people come to the city of Makkah, Saudi Arabia every year to perform Hajj (Islamic Pilgrimage) and Umrah. A cornerstone of Hajj and Umrah spirituals is to perform Tawaf, which is the circumambulation of the Ka'bah in the center of the Holy Mosque in Makkah. The areas of performing Tawaf (called Mataf) become very crowded during Hajj and the last ten days of Ramadan. This paper demonstrates how we utilized Global Positioning Systems (GPS) and Geographic Information Systems (GIS) to analyze pedestrian movement while performing Tawaf. During the Hajj of 1424 H (2004 in the Georgian Calendar), several GPS devices were used to collect pedestrian movement coordinates at specific time intervals. Computer software for tracking analysis is used to visualize and analyze the pattern of pedestrian movement in Tawaf. The software allows users to view temporal data, which can be set up with past time windows for historical data analysis. The findings of this research show levels of service and flow rates throughout different zones and times of Mataf. They indicate the most critical zones and times for Tawaf during Hajj. They also visually demonstrate the track pattern of pedestrian movement at different locations in the Tawaf area. The paper concludes with some redesign recommendations to remove obstacles and facilitate pedestrian movement in Tawaf. The approach described in this paper can be implemented in architectural and urban design space modifications to improve pedestrian movement in open spaces.

1. INTRODUCTION

According to Islamic literature, Ka'bah is the first house of worship built for mankind. It was originally built by Adam and then reconstructed by prophets Abraham and Isma'il (Holly Quran). It is a cube-shaped structure in the Holy Mosque that is located in central Makkah, Saudi Arabia. Muslims around the globe face Ka'bah in their five daily prayers. Tawaf is the circumambulation of the Ka'bah seven times (Figure 1). Tawaf is performed in Mataf areas at different levels. Millions of Muslims come to Makkah every year to perform Tawaf during Hajj (Islamic Pilgrimage) and Umrah. Tawaf is a cornerstone spiritual ritual of both Hajj and Umrah.

Figure 1. Tawaf: the circumambulation of the Ka'bah.
Courtesy: Hajj Research Institute.

Mataf areas become very crowded during Hajj period and the last ten days of Ramadan. Hajj occurs once per year in the twelfth month of the Islamic lunar calendar. Umrah occurs any time in the year but it reaches its height in Ramadan, the ninth month of the Islamic lunar calendar. During peak times the density exceeds all pedestrian-movement safety standards (more than six persons per square meter). The courtyard (Figure 2) of the Holy Mosque, the prime location for performing Tawaf, becomes completely congested. When the courtyard becomes very crowded, people go to upper floors to perform Tawaf (Figure 3). In such cases, they either use the first floor or the roof the Holy Mosque, escaping from crowds in the courtyard.

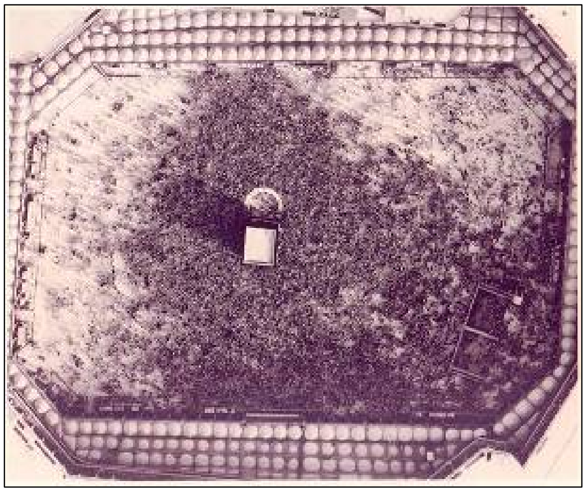


Figure 2. An aerial photograph of Tawaf in the courtyard.
Courtesy: Hajj Research Institute.

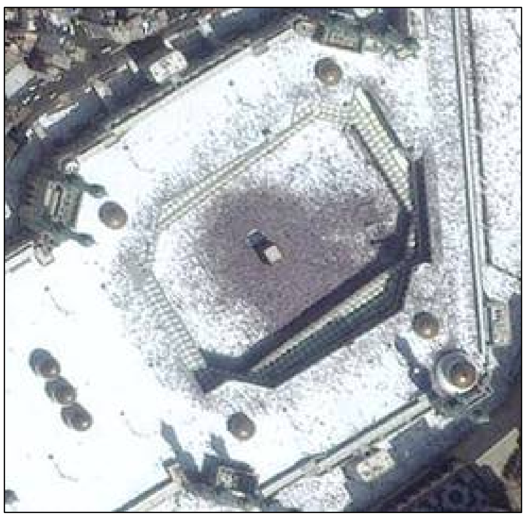


Figure 3. Performing Tawaf in the courtyard and on the roof of the Holy Mosque.
Courtesy: Space Imaging Middle East.

Tawaf requires careful research for future improvements and to avoid overcrowding. One important research direction is the investigation of the pedestrian behavior during Tawaf. Mush previous research has analyzed Tawaf, but this research lacks detailed and accurate spatial and temporal data. Most of this research was based on human visual observation from site, using video camera recordings. Such a technique is not accurate since it usually includes human errors.

The recent advances in Global Positioning Systems (GPS) receivers offer researchers new techniques for the analysis of human walking patterns (Ladetto et al., 2000). GPS technology offers a new level of accuracy for direct quantification of time–location activity patterns in assessment studies (Elgethun et al., 2002).

2. METHODOLOGY

This paper explores the use of GPS and GIS to analyze and understand the pedestrian movement pattern in Tawaf areas. First, spatial-temporal data were collected by trained students using GPS devices at different times. Second, GIS allowed spatial-temporal analysis of collected data. The following three subsections describe our methodology in detail.

2.1 Data Collection

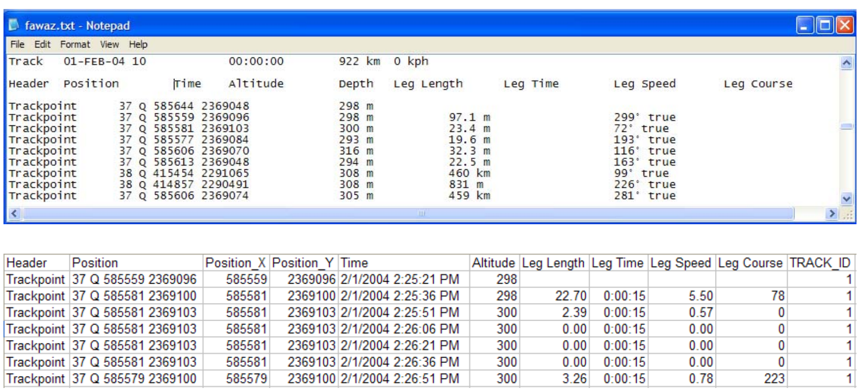
To capture data on pedestrian movement in Tawaf, students used GPS devices to collect position coordinates at 15-second intervals. These coordinates represent tracks of a person’s movement in Tawaf areas. These tracks (coordinates with time stamps) are needed for spatial temporal analysis. Time- and date-specific information for geographic locations enables the tracking of previously documented observations.

Each student simulates a person performing Tawaf. Four students have been trained on how to use the GPS devices and collect data from Tawaf areas, including the courtyard and the roof of the Holy Mosque. The second floor is covered with a concrete ceiling that prevents the GPS devices from receiving signals. That is why no data were collected on the second floor. During the Hajj of 1424 H (2004 in the Georgian Calendar), several GPS devices were used to collect pedestrian movement coordinates at specific time intervals. Trained students were also instructed to collected data during the tenth, eleventh, and twelfth days of Dhul-Hijja (the last month of the Islamic lunar year). The equivalent Georgian date of the 10th of Dhul-Hijja when the data is collected is the 4th of February, 2004. These three days bring the largest crowds to the Mataf areas. During each day, the students have to go for one round around the Kabah at the beginning of each hour, according to Table 1.

Track Number	**Start Time**	**Date**		
		10th	**11th**	**12th**
		Feb. 4	**Feb. 5**	**Feb. 6**
1	10:00 am	X		
2	11:00 am	X	X	
3	12:00 pm	X	X	X
4	01:00 pm	X	X	X
5	02:00 pm	X	X	X
6	03:00 pm	X	X	X
7	04:00 pm	X	X	X
8	05:00 pm	X	X	X
9	06:00 pm	X	X	X
10	07:00 pm	X	X	X
11	08:00 pm		X	X
12	09:00 pm			X

Table 1. GPS data collection schedule.

The data collected using the GPS receivers include position coordinates (latitude and longitude), time, leg length, leg time, leg speed, leg course, and a track identification number. The collected data then went through the process of format transformation (Figure 4) so it can be used to build a temporal geodatabase to represent Tawaf tracks.



```
fawaz.txt - Notepad
File  Edit  Format  View  Help
Track    01-FEB-04 10          00:00:00        922 km  0 kph

Header   Position       Time     Altitude      Depth   Leg Length    Leg Time     Leg Speed     Leg Course

Trackpoint      37 Q 585644 2369048            298 m
Trackpoint      37 Q 585559 2369096            298 m         97.1 m                299° true
Trackpoint      37 Q 585581 2369103            300 m         23.4 m                72° true
Trackpoint      37 Q 585577 2369084            293 m         19.6 m                193° true
Trackpoint      37 Q 585606 2369070            316 m         32.3 m                116° true
Trackpoint      37 Q 585613 2369048            294 m         22.5 m                163° true
Trackpoint      38 Q 415454 2291065            308 m         460 km                99° true
Trackpoint      38 Q 414857 2290491            308 m         831 m                 226° true
Trackpoint      37 Q 585606 2369074            305 m         459 km                281° true
```

Header	Position	Position_X	Position_Y	Time	Altitude	Leg Length	Leg Time	Leg Speed	Leg Course	TRACK_ID
Trackpoint	37 Q 585559 2369096	585559	2369096	2/1/2004 2:25:21 PM	298					1
Trackpoint	37 Q 585581 2369100	585581	2369100	2/1/2004 2:25:36 PM	298	22.70	0:00:15	5.50	78	1
Trackpoint	37 Q 585581 2369103	585581	2369103	2/1/2004 2:25:51 PM	300	2.39	0:00:15	0.57	0	1
Trackpoint	37 Q 585581 2369103	585581	2369103	2/1/2004 2:26:06 PM	300	0.00	0:00:15	0.00	0	1
Trackpoint	37 Q 585581 2369103	585581	2369103	2/1/2004 2:26:21 PM	300	0.00	0:00:15	0.00	0	1
Trackpoint	37 Q 585581 2369103	585581	2369103	2/1/2004 2:26:36 PM	300	0.00	0:00:15	0.00	0	1
Trackpoint	37 Q 585579 2369100	585579	2369100	2/1/2004 2:26:51 PM	300	3.26	0:00:15	0.78	223	1

Figure 4. GPS data at different stages of transformation.

2.2 Building a Temporal Geodatabase

A geodatabase was created to capture both a base map and the collected GPS data. First, a base map (Figure 5) feature class was created to represent features of the Holy Mosque, including the Ka'bah, courtyard, and roof. The court was then divided into seven zones (Figure 5) according to different activities. Second, the transformed GPS data were imported into this geodatabase. Then several temporal layers were created to represent different pedestrian movement tracks at various times and locations.

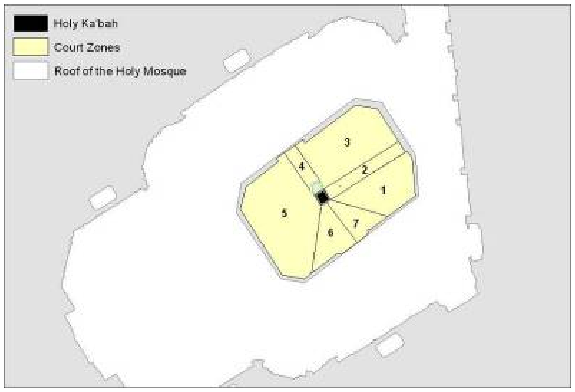


Figure 5. Base map repressing Ka'bah, the court zones, and the roof.

2.3 Spatial-Temporal Analysis

To understand the human walking behavior in Mataf areas in the court and on the roof of the Holy Mosque, it is important to perform tempo-spatial (time-location) analysis of the data collected with the GPS devices.

Tracking analysis software can visualize complex time series, spatial patterns, and interactions while integrating all other GIS data. The software allows users to view and analyze existing temporal data, which can be set up with past time windows for historical data analysis. Such software can be used to visualize the pattern of pedestrian movement in Mataf areas. In this research, we used ArcGIS Tracking Analyst software to perform the spatial-temporal analysis of Tawaf. Figure 6 shows the track points of three different days (10th, 11th, and 12th of Thul-Hijja) in the courtyard and on the roof. In this figure the track points are colored according to different days. Each track point takes a color according to the day to which that track belongs. From this figure we can see the different paths of movement a pedestrian can take on the two levels.

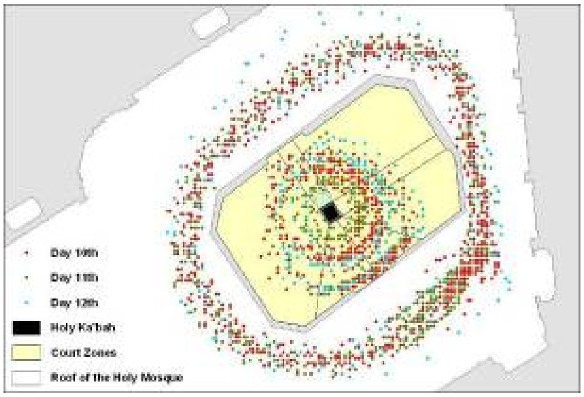


Figure 6. Track points of three different days (10th, 11th, and 12th of Thul-Hijja) in the courtyard and on the roof.

From the GPS data, the track points are represented by different colors according to speed of the person performing Tawaf. Figure 7 shows the tracks of pedestrian movement in the courtyard. Each track point is color-coded according to the speed of the walker, ranging from red (slow) to green (fast). The figure shows the level of service at various locations based on speed representation. Figure 8 demonstrates pedestrian speed at different locations in Tawaf and on the roof of the Holy Mosque.

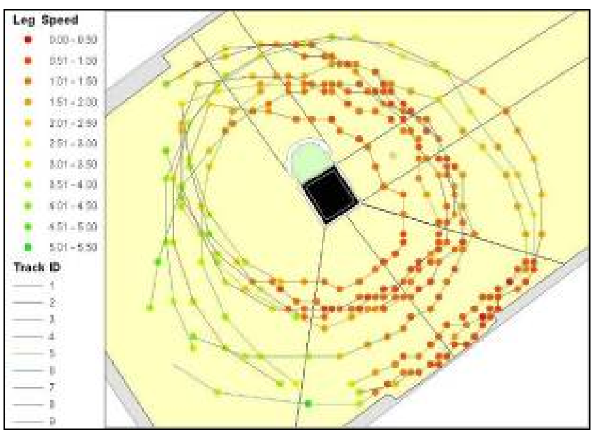


Figure 7: Comparing speeds of different tracks in the courtyard.

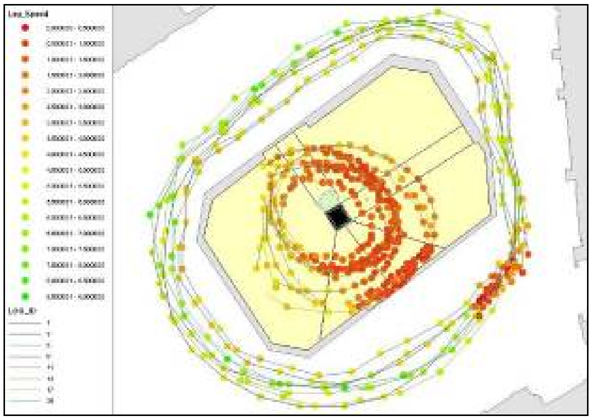


Figure 8. Pedestrian speed at different locations in both the courtyard and on the roof.

Another important observation (Figure 9) is that the pattern of movement changes according to level of congestion. Smooth tracks, represented as smooth lines, show ease of movement. Tracks represented as staggered lines show movement in more congested areas. This is another benefit of representing the paths of movement using GIS and GPS.

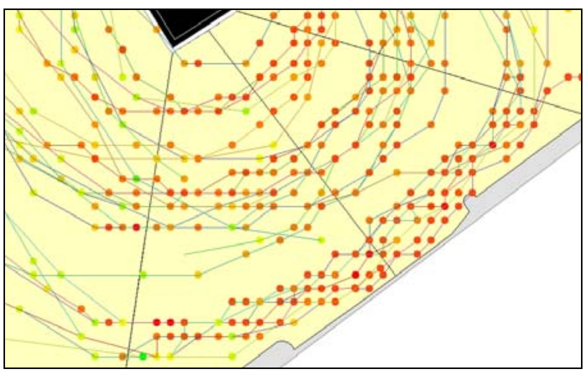


Figure 9. Track lines representing pedestrian staggered movement at crowded areas.

Figures 10, 11, and 12 show how the use of Tracking Analyst Playback Manager (part of the Tracking Analyst software) allowed us to control settings for different ways of displaying and replaying temporal data. The Playback Manager can be used to monitor changes in spatial data within a specific time window. Figure 10 shows the movement of a pedestrian at different times by moving the indicator across the bar of a specified time window.

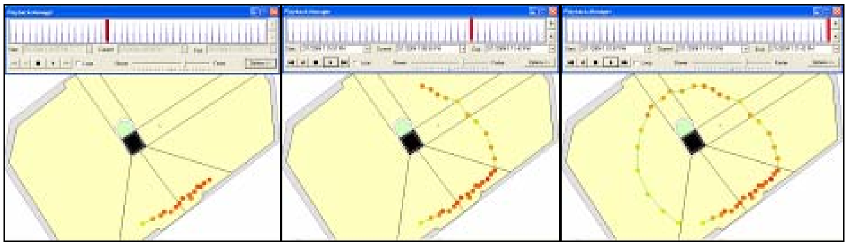


Figure 10. Visualizing pedestrian movement by animation and with a time bar.

Through generated animations by the Tracking Analyst, a simultaneous comparison of pedestrian movement in the court and at the roof of the Holy Mosque is shown in Figure 11. This shows the difference of movement pattern and speed at various locations. This approach can be utilized to compare movement according to different architectural or urban design environments for evaluation purposes.

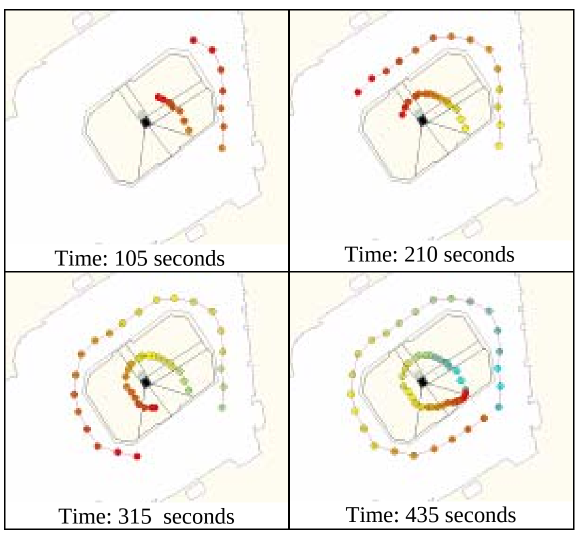


Figure 11. Animating pedestrian movement at both levels simultaneously.

Another important spatial-temporal visualization can be performed in a past time window. In this visualization track, each point's color changes as time passes. For instance, a dark red track point shows that a long time has passed from the start of a pedestrian movement. A dark blue track point indicates that no time has passed since the start of a pedestrian movement. Figure 12 uses this visualization approach to see how long a pedestrian takes (despite the speed) to finish his/her Tawaf at both levels (in the courtyard and on the roof). In this figure, surprisingly, the person performing Tawaf on the roof had completed one round before the person performing Tawaf in the courtyard, even though the distance around the roof is longer. This is because the court becomes so crowded so that the pedestrian movement is slowed down.

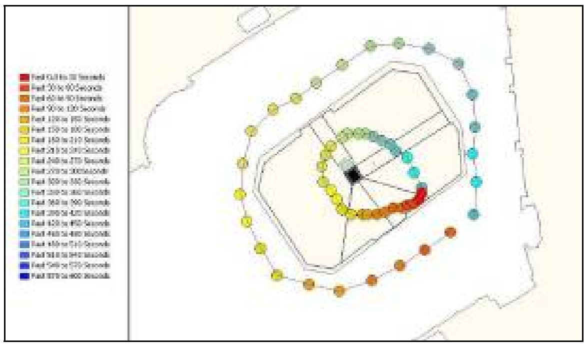


Figure 12. Comparing pedestrian movement time in the courtyard and on the roof in a past time window

3. RESULTS

The above spatial-temporal analysis shows how an architect or urban designer can better visualize and understand pedestrian behavior in various architectural and urban environments. The following section presents some of the results of this spatial-temporal analysis.

The above spatial-temporal analysis depicts the specific characteristics of pedestrian movement in Tawaf. Figure 13 defines the levels of service and flow rate in different zones of Tawaf in the courtyard. This done by using a geoprocessing technique that takes all track points and superimpose them upon the layer that determines the different Tawaf zones that were described in Figure 5. After the overlay has been performed, each zone has the average pedestrian speed of all track points. Figure 13 shows the average speed at different zones of Tawaf in the courtyard during Hajj. Zone 7, for instance, is the most crowded area, and Zone 5 is the least crowded area.

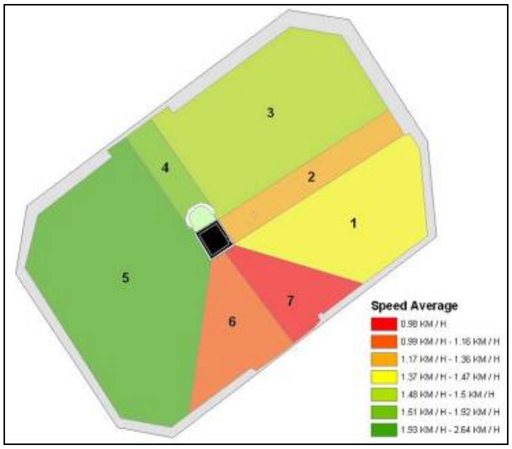


Figure 13. Color-coded map showing the pedestrian average speed at different zones in the courtyard.

Pedestrian average speed in each of the seven zones in the court for each day (10th, 11th, and 12th days of Dhul-Hijja) is shown in Figure 14. Each zone is represented in three columns to represent the three days. Each column indicates the average speed on a particular day. For instance, the slowest average speed was on the 10^{th} day of Dhul-Hijja in Zone 7 (0.86 Kilometres per Hour). The fastest average speed was on the 10^{th} day of Dhul-Hijja in Zone 5 (2.94 Kilometres per Hour).

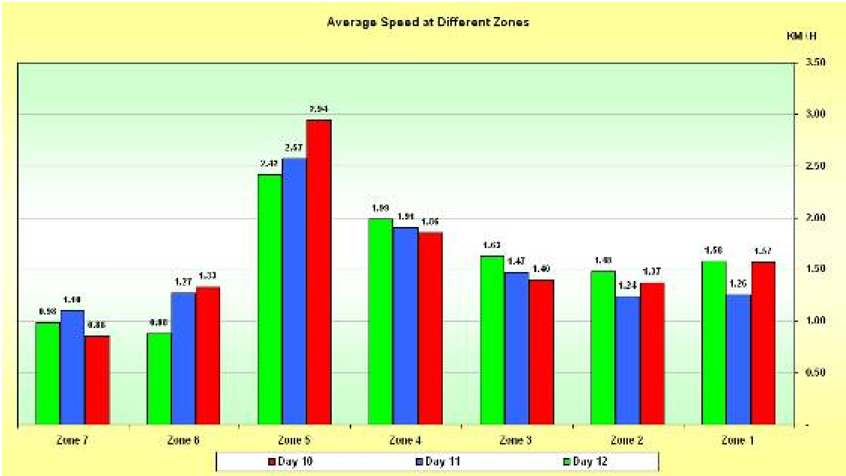


Figure 14. Pedestrian average speed in different zones in the courtyard on each day.

Throughout the three days, pedestrian average speed in different zones of the courtyard is shown on a graph (Figure 15). Each zone is represented as one column to show the average speed across the three days. The slowest average speed was on the 10th day of Dhul-Hijja in Zone 7 (0.98 Kilometres per Hour). The fastest average speed was in the 10th day of Dhul-Hijja in Zone 5 (2.64 Kilometres per Hour).

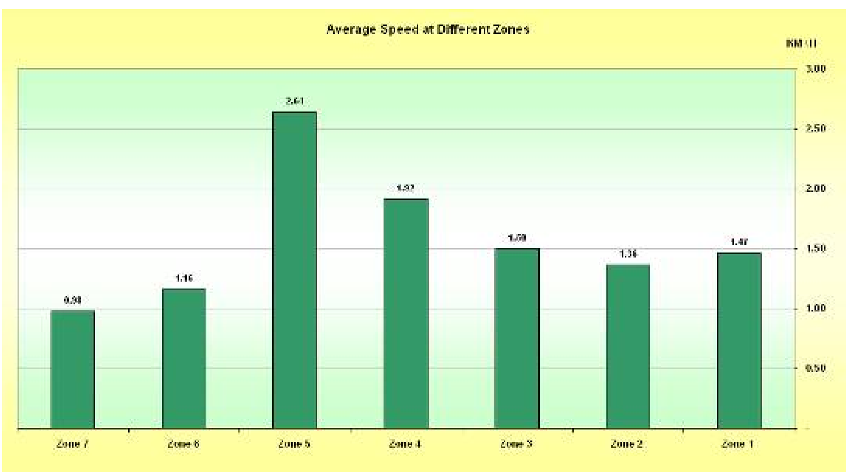


Figure 15. Pedestrian average speed at different zones of the court on all three days.

The results of this research show that Zone 7, which is located before the Tawaf start line, is the most crowded area. This is because pedestrians intend to stop or search for that line before each round while performing Tawaf. This line was added few years ago to mark the beginning of Tawaf, but it slowed down the movement of people in that zone. The slowness of movement in this zone also affects the preceding area, Zone 6.

4. CONCLUSIONS

The above spatial-temporal analysis shows how an architect or urban designer can better visualize and understand pedestrian behavior in various architectural and urban environments. This research demonstrates how GPS and GIS can be utilized to perform tempo-spatial analysis of human walking behavior in an architectural or urban open space. Tawaf areas were used as a case study since they becomes very crowded during Hajj. Many researchers have analyzed pedestrian movement in Tawaf, but none have employed GPS and GIS to examine their use in such analysis. The paper has demonstrated is the validity of using GPS collected data to better understand pedestrian behavior in Tawaf. Such analysis is very useful in design decisions and in making improvements upon architectural and urban environments such as Tawaf areas. The paper has shown that some obstacles need to be removed to facilitate pedestrian movement in Tawaf area in the courtyard and on the roof. One such obstacle is the beginning line of Tawaf which delays pedestrian movement, as shown in Figure 13.

Based on the above spatial-temporal analysis, this research highly recommends removing the Tawaf start line. In 2005, the Saudi government decided to remove the line. This research was one factor that affected this decision. Now, the line is no longer there and Tawaf becomes much smoother at the removed line location.

For future work, more GPS devices should be used to verify the accuracy of collected data. In addition, certain measures have to be added to ensure data integrity. Future researchers should obtain real-time data from site to perform real-time analysis. This can be done by adding an information carrier device that directly transfers the GPS data to a computer via Short Messaging System (SMS), Radio, or General Packet Radio Service (GPRS). Another line of future work is to do a comparative analysis after removing the start line of Twafa.

This paper has shown how spatial-temporal analysis using GPS and GIS can enable architects and urban designers to better visualize and understand pedestrian behavior in various architectural and urban open spaces.

5. ACKNOWLEDGMENTS

The authors would like to thank Moatasem Badawai for his keen supervision and training of students on using the GPS devices for data collection. Moatasem Badawi is a student at the Electrical Engineering Department, College of Engineering and Islamic Architecture, Umm Al-Qura University, Makkah, Saudi Arabia.

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[1] N. A. Koshak and A. Fouda, "Analyzing pedestrian movement in Mataf using GPS and GIS to support space redesign," in Proc. 9th Int. Conf. on Design and Decision Support Systems in Architecture and Urban Planning, Leende, the Netherlands, July 2008. UNC research on crowd simulation. This WWW site has pointers to the papers that describe the algorithms used in our simulation. Geographic Information Systems (GIS) and related spatial analysis methods are quite adept at handling spatial dimensions of patterns and processes, but the temporal and coupled space-time attributes of phenomena are difficult to represent and examine with contemporary GIS. (Dr. Paul M. Torrens, Center for Urban Science + Progress, New York University).Â Space-time cubes and animations are classics when it comes to visualizing movement data in GIS. They can be used for some visual analysis but have their limitations, particularly when it comes to working with and trying to understand lots of data.Â (Some notable exceptions of formats that do support time by design are GPX and NetCDF but those arenâ€™t really first-class citizens in current desktop GIS.)