Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

DATA-DRIVEN SIMULATION OF URBAN HUMAN MOBILITY CONSTRAINED BY NATURAL DISASTERS

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ABSTRACT

Understanding of human movements in urban areas plays a key role in improving our disaster response, evacuation, and relief plans. However, there is a lack of research on human mobility perturbation under the influence of hurricanes. Furthermore, limited simulation studies have had access to empirical human travel data in urban areas during natural disasters. In this paper we developed a computational model to simulate human mobility during the approaching and strike of hurricanes. Inspired by animal movements in a fragmented habitat, we examined human movements in New York City and its adjacent areas during the striking of Hurricane Sandy. Based on the patterns observed, we established a data-driven model to simulate human movements during hurricanes. The model integrated multiple resources of urban informatics including U.S. census data, Twitter data, and Google Maps. The research effort aims to inform policy-makers and support decision-making under different emergency situations that can arise during hurricanes.

1 INTRODUCTION

Cities are facing an increasing amount of threats from natural disasters. Natural disasters cause significant disruption on human society and damages on buildings and infrastructure. A 2013 report from UNISDR (2013) summarized that from 2002 to 2012, natural disasters caused 1.2 million deaths, influenced 2.9 billion people, and resulted in a total of 1.7 trillion dollars of economic loss. It is predicted that the numbers will increase due to on-going climate change. Humans are facing an ever-pressing challenge to remain resilient during natural disasters.

Current disaster response and evacuation plans are not effective enough. Take New Yorkers' actions during Hurricane Sandy as an example. While 71 percent of the New Yorkers living in evacuation areas were aware of the mandatory order to evacuate, more than 50 percent of them stayed nonetheless (Schuerman 2013). Regretfully, many of the fatalities occurred in the evacuation areas (CDC 2013). Even the people who evacuated were not entirely safe. Data from FEMA (US Federal Emergency Management Agency) show that the flooding areas in NYC during Hurricane Sandy were 15 percent larger than the evacuation areas, putting people who stayed in some of the assumed safe areas in severe threat (Rosenzweig and Solecki 2014).

Existing research has already pointed out that human mobility plays a key role in disaster evacuations (Pan et al. 2007; Schneider et al. 2011). A bottom-up understanding of human mobility can help reduce the reoccurrences of traffic jams during emergencies. Furthermore, deep understanding and accurate prediction of human mobility can potentially save lives. In the case of Hurricane Sandy, if we could have identified and predicted susceptible individuals and provided critical information, their lives may have been saved.

Despite the critical importance of human mobility, studies of human mobility perturbation under the influence of natural disasters are limited (Horanont et al. 2013; Wang and Taylor 2014, 2016). Current studies and models explicitly or implicitly assume that human movements happen in a continuous space without considering constraints and/or gaps. Such an assumption may not hold true during the occurrence of natural disasters. Many situations can cause gaps in space, such as road blocks, traffic jams, evacuation zones, and so on. These gaps can force people to change their routine movement trajectories.

To predict the influences and changes is a difficult task. Natural disasters are extreme events and we often do not have enough cases to make the prediction. Therefore, this study develops a bottom-up data-driven simulation platform. The platform integrates different data resources to simulate the potential perturbation on urban mobility. The platform can serve as a testbed to study different scenarios during the occurrences of natural disasters.

2 BACKGROUND

Researchers have attempted to describe animal movement patterns for over one hundred years. Pearson (1905) first proposed a mathematical model to capture human and animal movements. This model stated that an individual moves consistently where each movement has a set distance, but a randomly different angle from its previous movements. Such a model is called a random walk model. Later on, Lévy modified the model and made the distances of steps follow a heavy-tailed probability distribution such as a power-law (Mandelbrot 1983). This model was called a Lévy flight. Research has shown that the movements of many types of animals follow Lévy flight patterns (Bartumeus 2007; Benhamou 2007; Viswanathan et al. 1996).

Lévy flights observed in animal movements have inspired studies in human mobility. Brockmann et al. (Brockmann et al. 2006) was an early researcher that studied human mobility using a large quantity of empirical data. Using the travel distances of 464,670 one-hundred-dollar bills, the study confirmed that human mobility follows the Lévy flight model. The truncated power-law distribution governs human mobility, and the exponent value was found to be around 1.59. Such findings have been supported by multiple subsequent studies with exponent values ranging from 1.59 to 1.88 (Brockmann et al. 2006; Cheng et al. 2011; González et al. 2008; Hawelka et al. 2013).

Undoubtedly an important discovery, Lévy flight patterns may not always be the best model to describe animal movements. An assumption of Lévy flights, though it may not be explicitly pointed out by researchers, is that animal movements happen in a continuous space without any constraints. In reality, animals' habitats and foraging spaces always have boundaries. It is also evident that human activities have imposed more constraints and limitations to animal spaces. All of these constraints can make the Lévy flight pattern an inappropriate model to describe animal movements.

One example where human activity influences animal movement is habitat fragmentation. Habitat fragmentation is the process where a large habitat is transformed into several smaller patches. These patches become isolated from each other, and the total area of these patches is always smaller than that of the original habitat (Wilcove et al. 1986). Habitat fragmentation was observed to be associated with different types of long-term effects such as population reduction and extinction, edge effects, and reduced gene flows (Wolff et al. 1997). Research has shown that habitat fragmentation can dramatically change animal movements as a short-term effect (Diffendorfer et al. 1995). Laurance et al. (2004) studied how roads and human clearing influenced birds' movements. They found while there were no physical constraints that prevented birds from flying near or crossing the roads built inside of forests, birds avoided doing so due to edge and gap avoidances. In fact, comparing two areas of the same size, one in a forest and one crossed by a road, the number of movements reduced by 50% in the latter case.

While mainly observed in animals, similar fragmentation can happen in human societies as well. As mentioned before, such fragmentations are particularly common during the occurrence of natural disasters.

Different situations, such as road blocks, traffic jams, evacuation zones, disaster damaged areas, etc., can fragment urban spaces. In these emergency situations, urban dwellers may find it difficult to cross these gaps and be forced to reduce their activities to a smaller area, and/or be denied to the primary locations they visit in ordinary days. All of these can cause constraints to human movements.

Inspired by habitat fragmentation and its influence on animal movements, this study examines whether this phenomenon in built environments has a similar influence on human movements. Using a case study of Hurricane Sandy, the research attempts to discover whether evacuation zones separated New York City from its adjacent areas. Though not as effective as expected, the mandatory evacuation areas forced many New Yorkers to leave the area and prohibited people from going back or passing by it. Technically, it separated New York City from the adjacent land. We examined if such separations influenced movements crossing the gaps and simulated its impact on urban mobility. Such understanding will not only reveal a critical pattern of human mobility perturbation under the influence of natural disasters, but also potentially improve our ability to predict human movements in similar situations through computational simulation.

3 URBAN FRAGMENTATION ANALYSIS

We collected human movement data from New York City and its adjacent areas during Hurricane Sandy. The data was then analyzed to identify any perturbation caused by habitat fragmentation.

3.1 Data Collection

Human mobility data were collected from Twitter. We used Twitter's open API and created a continuous connection between a computer in our research lab and a streaming endpoint at a Twitter server. The connection continuously downloaded tweets in real-time. Each public tweet was collected if the tweet had both geolocation information, also known as being geo-tagged, and if the coordinates were within 74˚15'W to 73˚40'W longitude and 40˚30'N to 40˚57'N latitude, the range of coordinates that contains the studied area. The data collection started around 4pm on October 29th and lasted for 12 days. Every tweet included: the text information, the tweet's ID, the name and ID of the user who posted the tweet, the time stamp for when it was posted, and its coordinate location. More details about the data collection process can be found in Wang and Taylor (2015).

3.2 Data Analysis

We analyzed NYC data and determined both the total displacements and the crossing displacements during and after Hurricane Sandy. A displacement is the distance between two consecutive locations of the same user. A crossing displacement occurs when the starting point of a displacement is within NYC with its corresponding end point located outside of NYC, or vice versa. The distance was calculated using the Haversine formula shown in Equation 1 (Robusto 1957):

$$d = 2r \times \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos\phi_1 \cos\phi_2 \sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right)}\right)$$

Where r is the earth's radius, which approximately equals to 6,367,000 meters, ϕ is the latitude, and φ is the longitude. We used ArcGIS and its associated Python package arcpy to conduct our analysis.

4 DATA-DRIVEN SIMULATION BASED ON EMPIRICAL RESULTS

Figure 1 shows the ratio of crossing displacement divided by total displacements for the 12 days during and after the landfall of Hurricane Sandy. We found no significant changes in the total displacements during the strike of Hurricane Sandy. In fact, the total displacements increased by 19% during the first 24-hours after the landfall of Hurricane Sandy. However, the ratio was dramatically reduced, and the ratio was down by more than 50%.

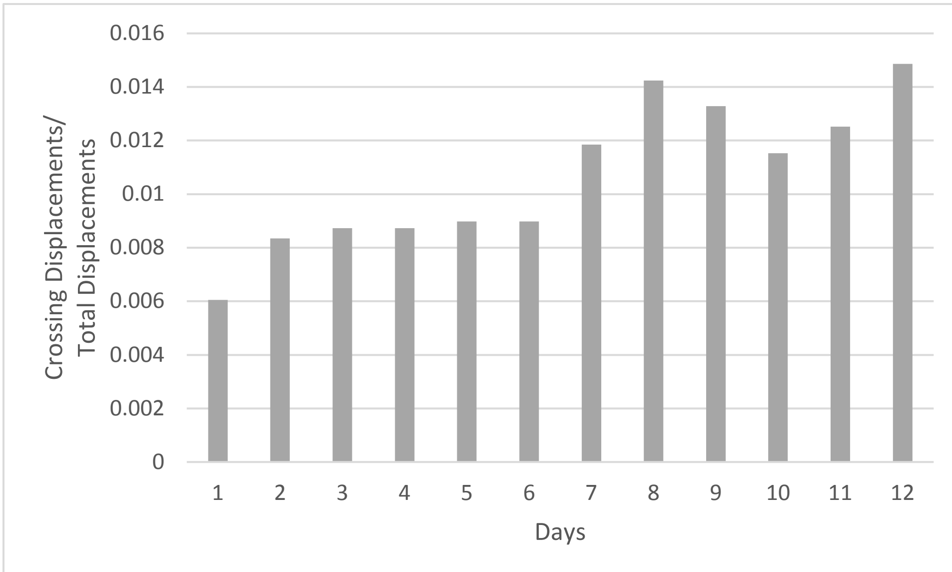

Figure 1: Geographical distribution of crossing displacements.

The crossing displacements gradually recovered to its steady state level. The phenomenon reflected the infrastructural situations in New York City. Hurricane Sandy caused flooding in several tunnels and a widespread power outage. Most public transportation systems did not resume partial or full scheduled service until 36 to 72 hours after Hurricane Sandy struck (Kaufman et al. 2012), and over 1 million people in the city were still without power until 2pm Nov. 2 (McGeeham 2012).

After discovering how urban fragmentation during emergency situations can influence human mobility, we developed a data-driven simulation model. Research has shown that simulations play a key role in the study of human mobility during an emergency situation (González et al. 2008). The analytical results and large scale data of human movements enable the possibility to build a data-driven model to simulate human mobility during the occurrences of hurricanes and typhoons. Therefore, we propose a human mobility simulation platform based on multiple resources of urban informatics including U.S. census data, Twitter and Google Maps.

The model is built in three steps. First, we simulated 20,000 locations in NYC as one end of the daily commuting. Rather than randomly select places, we analyzed the visited locations from Twitter data. The visitation frequencies of the locations were ranked, and the most visited locations were selected. To avoid over concentration of the selections, any pair of locations needs to be at least 100 meters apart from each other. Then we simulated the other end of the daily commuting. To find the commuters around the NYC area, we used the U.S. census data for commuters. We retrieved the numbers of commuters from the counties that are within 100 miles around NYC. To simplify the model, we used ArcGIS to find each county's centroid. It is assumed that all commuters in this county will start their travels at the centroid. A total of 1.3 million commuters from 4,726 counties were covered in this model. In the last step, we reconstructed the paths of commuting. We used the Google Maps Matrix API to conduct the simulation. The codes were developed in Python by using the *geopy* and *googlemaps* packages. By inputting the starting and ending geographical coordinates and specifying the transportation mode, Google Maps API will return the optimized travel routes. To simplify the simulation, we only used driving as the traveling mode. Figure 2 shows one step of the simulation result returned from Google Maps API.

```
…
u'steps': [
      {u'html_instructions': u'Head <b>north</b> on <b>
            Hunt Ave</b> toward <b>Morris Park Ave</b>',
      u'distance':
            {u'text': u'253 ft', u'value': 77},
      u'travel_mode': u'DRIVING',
      u'start_location':
            {u'lat': 40.8447536, u'lng': -73.8649629},
      u'polyline':
            {u'points': u'unhxF~vyaMeCp@'},
      u'duration':
            {u'text': u'1 min', u'value': 17},
      u'end_location':
            {u'lat': 40.8454227, u'lng': -73.865207}
      },
```


Figure 2: Simulation Result from Google Maps API.

Figure 3 show the results of the simulation. The green lines represent the simulated routes of all the travels. It is observed the simulation generally reconstructed the travels along the highway system around NYC (left panel of Figure 3) as well as the finer road networks inside the city (right panel of Figure 3). We overlaid the routes on the flooding map during Hurricane Sandy. Adding the number of population on the routes, we found that the flooding area impacted about 50% of the commuters which aligns with the impact we observed from the empirical data.

The study provides a test bed for potential influences of natural and manmade disasters. Computational experiments can be conducted to test different scenarios. These scenarios include: (1) the imposition of evacuation orders, (2) the occurrences of flooding and other natural disruptions, and (3) the abrupt failure of infrastructure that can cause road blockage, bridge collapse, power outages, etc. We conducted an experiment for the first scenario to analyze how different evacuation plans can impact urban mobility in NYC. After Hurricane Sandy's strike, the NYC government updated their evacuation plan during hurricanes. The new plan has 6 evacuation zones based on the significance of the natural disasters. We simulated the consequences of the enforcement of each evacuation zone and how many commuters will be influenced. Following the similar procedures described before, we found that about 21% to 71% of all the commuters will be influenced based on difference levels of evacuation enforcement.

Figure 3: Commuting Simulation around the NYC.

5 CONCLUSIONS

Natural disasters can significantly influence human activities and impose constraints on human mobility. One such influence is caused by habitat fragmentation. When natural disasters occur, they often force people to stay away from certain land areas due to present or potential damages. Even small gaps in the human habitat can cause significant perturbation in routine urban travels. While habitat fragmentation has not been examined in human movements, it has gained much attention in animal movements (Laurance et al. 2004). Research has examined how habitat fragmentation can influence movement patterns from different animals (Diffendorfer et al. 1995).

Inspired by these studies, this study examined whether such a phenomenon could be observed in human mobility. Using Hurricane Sandy as a case study, we retrieved human mobility data and analyzed the crossing displacements around the New York City area. We found that evacuation zones caused habitat fragmentation and substantially influenced human movements across these gaps. Crossing displacements reduced to approximately half the amount observed in normal states. The influence of habitat fragmentation gradually diminished when the city recovered from the hurricane.

The study confirmed that habitat fragmentation can significantly influence human mobility. To predict human mobility during natural disasters, the urban constraint is a key factor that needs to be considered. Therefore, we proposed a data-driven simulation testbed. The testbed incorporates urban fragmentation and can simulate human mobility in different scenarios. The simulation work will help us explore the impact of habitat fragmentation in urban areas to improve our understanding of human mobility patterns under the influence of natural and manmade disasters.

ACKNOWLEDGMENTS

This study is supported by the National Science Foundation under Grant No. 1142379 and a Virginia Tech BioBuild IGEP grant. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or Virginia Tech. Boston Area Research Initiative and the Center for Geographical Analysis at Harvard University also provided key data and computational resources that made this study possible.

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