Assessing Mobility Disruption From Hurricane Ida: A Comparative Analysis of Urban, Suburban, and Rural Counties Using Digital Footprint DataState in the Black Hole Binary GRS 1915+105

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The large-scale flooding in the wake of Hurricane Ida in September 2021 severely disrupted movements and the delivery of essential services across the Northeast US. Understanding how communities are affected in terms of travel patterns over diverse geographic categorizations is essential for planning emergency actions and equitable recoveries. This study hence analyzes the mobility effects of Hurricane Ida by examining anonymized digital footprint data (SafeGraph) monitoring weekly and daily visits to Points of Interest (POIs) across select urban (New York County, NY; Philadelphia County, PA), suburban (Passaic County, NJ; Somerset County, NJ), and rural/suburban mix (Bucks County, PA; Chester County, PA) counties. We contrast flood-week (August 30th - September 6th, 2021) visits with visits recorded during a pre-flood baseline and subsequent post-flood recovery periods within five weeks; POIs are categorized by NAICS codes. Our analysis reveals steep declines in POI visitation across all county types, with particularly acute disruptions in urban centers and uneven recovery patterns across suburban and rural areas.

1. Introduction

Upon Hurricane Ida making landfall at Category 4, the storm moved northeastward, trailing severe floods across New Jersey, New York, and Pennsylvania between September 1st and 2nd, 2021 (1). While its wind intensity reached peak levels at the time of landfall, the remnants of Hurricane Ida dropped catastrophic floods further inland in urban centers of the Northeast. The flooding prompted loss of life and widespread property damage. For instance, New Jersey reported 29 deaths, mainly from flash flooding. The storm also caused extensive property damage and severe interruptions to daily life within these densely concentrated states (1, 2). Events such as these reveal the growing exposure of developed regions to episodes of extreme weather linked to climate change.

One of the consequences of major flooding is the disruption of human mobility, specifically impeding connection to essential services, hindering commutes to work, and obstructing emergency response, all of which compromise community resiliency and the recovery process (3, 4). Although prior studies have focused on hurricane preparedness and evacuation through surveys (5-7), and while other recent work has leveraged mobility data to analyze large-scale evacuation flows, the near-real-time impact on daily commute patterns using digital footprint data has yet to be thoroughly investigated. In particular, the actual impacts of travel disruptions can be measured from the change in visitation frequency to community POIs during and after the event. Furthermore, the disruption impacts are unlikely to be uniform and are therefore prone to vary significantly across geographic categorizations (urban, suburban, and rural) due to differences in infrastructure, population density, and accessibility to resources (8, 9). This concept of differential vulnerability is critical, as pre-existing social and infrastructural disparities directly shape a community's capacity to respond and recover.

This paper investigates the mobility effects of Hurricane Ida using anonymized digital footprint data from SafeGraph. It focuses on weekly and daily POI visitation patterns across six selected counties in New Jersey, New York, and Pennsylvania, representing a spectrum of urbanization levels: urban (New York County, NY; Philadelphia, Pennsylvania), suburban (Passaic County, NJ; Somerset County, NJ), and a mix of rural/suburban (Bucks County, PA; Chester County, PA). The five-week-long analysis covers two weeks before Hurricane Ida, the week of the storm (August 30th-September 6th, 2021, with Ida's major impacts occurring on September 1-2), and two weeks post-event. POI categorization is done according to the North American Industry Classification System (NAICS) to provide more unfiltered insight.

Using statistical analysis, primarily focusing on visitation changes, this research intends to: (a) characterize the immediate disruption to POI visits during the Ida flood event concerning the pre-flood baseline in the selected counties, (b) contrast the magnitude and patterns of these disruptions to mobility across the designated urban,

suburban, and rural/suburban-mix county categories, and (c) investigate visitation changes and recovery trajectories for selected NAICS-defined POIs (e.g., retail trade, accommodation and food services, and healthcare) during and after the flooding event.

By using statistical analysis, this study aims to provide a more refined perspective of the tangible impacts of a significant flood event on community mobility in contrasting landscapes. These findings are meant to feed into better disaster preparedness strategies, incident-focused response efforts, and recovery planning with equity considerations due to increasingly hazardous climate risks.

2. Materials and Methods

To achieve the end goals of this analysis, our research team developed a procedure that efficiently and accurately encapsulates human mobility during extreme events. Isolating the data into three different urbanization categories in the Northeast (urban, suburban, rural) to assess transportation and recovery allows for a more widespread understanding of how the event impacts different types of communities and gives additional potential for comparing/contrasting the effects of the event. Two urban counties were selected (New York CO, NY; Philadelphia CO, PA), along with two NJ suburban counties (Passaic CO, NJ; Somerset CO, NJ), and two PA suburban/rural counties (Bucks CO, PA; Chester CO, PA).

The selection of these counties was determined by three main criteria: location, damage, and extent of flooding.

Although Hurricane Ida most heavily impacted Gulf Coast states like Louisiana, this study focuses on the Northeastern United States due to the storm's uniquely disruptive impact on transportation infrastructure in a region that does not experience severe weather often. This relative lack of preparedness led to a greater disruption of critical infrastructure such as subways, roads, and rail networks. Because this research centers on the impact of extreme weather on human mobility, Ida offers a valuable case to examine transportation impacts and response in a region of the United States that is unaccustomed to severe weather. Limiting this study to the Northeast reduces the potential for any variability introduced by differences in storm strength, geography, and emergency response systems across regions. Additionally, focusing on a single region helps minimize cultural and socioeconomic disparities; for example, since the Gulf Coast and the Northeast differ significantly in culture and demographics, focusing solely on one region helps improve the consistency and comparability of the data.

Another consideration was the total damage inflicted by the event. Using the NOAA Storm Events Database, only counties with property and/or crop damage totals from Hurricane Ida exceeding $1 million were selected as potential fits.

Finally, the extent of flooding was also considered. Accessing Sentinel Hub satellite data from late August to early September 2021 (Hurricane Ida timeframe) and using it to identify regions where water is abnormally present, such as an overflowed river, or a body of water that is not present in typical conditions, created a dynamic model that illustrates where the event caused flooding to occur. Only counties exhibiting widespread flooding were considered. By combining all three criteria, the six counties previously stated were selected as focus counties to delve deep into visitation and mobility records during Ida.

To evaluate the impacts of travel disruptions, calculating the change in visits to community POIs from the weeks leading up to the event compared to during and after the event is vital. We decided to focus on a five-week range: two weeks prior to the event, the week of the storm, and two weeks following it. This range provides insight into visitation patterns to local POIs, including baseline levels, and changes during preparation, the event, and recovery. Understanding these tangents allows for a comprehensive assessment and analysis of how human mobility changes over the course of a disaster. Our research team utilized digital footprint data from SafeGraph, a company that provides anonymized location data from mobile device applications, which illustrated the visits of the population to POIs such as restaurants, hospitals, or grocery stores. Each POI is classified by the North American Industry Classification System (NAICS), the standard used for classifying business establishments by federal statistical agencies (10), which is based on their primary activity such as restaurant or gasoline station. This data was extracted by county and week in the form of a 'CSV' file detailing all POIs and the visits each experienced over time. Data analysis was conducted in Python via Google Colab notebooks, applying linear regression with controls for day-of-week effects and outliers. A refined regression analysis along with other statistical tests (i.e., t-tests) were executed to analyze this data and discover trends in visitation records. Our regression model created a baseline measure for each POI (pre-Ida average visits) and utilized it to calculate normalized visits based on this baseline (i.e., ratio of visits based on pre-Ida baseline). The model created dummy variables to represent the relevant time periods surrounding the event: during-Ida, post-Ida, and the weekend. Isolating weekends is important, as travel behavior during that time is significantly different from that of weekdays (11). Adding on, our model also created a 7-day recovery period for more specific analysis, removed outliers for a more robust regression, and calculated the Variance Inflation Factor (VIF) to check for multicollinearity. A few statistical trends were anticipated and observed, such as the quantity of visits being higher leading up to the

event with consideration to preparedness, a sharp decrease on the day of the event and in the days succeeding, and a slow increase as recovery commences. These statistical trends are a great representation of the change in human mobility over the course of Hurricane Ida, and linking it with socioeconomic factors from the U.S. census (12) allows for a comprehensive evaluation to be performed on equity impacts and recovery across all three urbanization types across the Northeast.

3. Results

3.a) At the end of data analysis, it was determined that visitation and travel trends were disrupted by the remnants of Hurricane Ida as it passed over locations in Pennsylvania, New Jersey, and New York on Wednesday, September 1st and Thursday, September 2nd, 2021. The analysis included urban (New York City, NY; Philadelphia, PA), suburban (Passaic, NJ; Somerset, NJ) and rural/suburban mix (Chester, PA; Bucks, PA) communities in the three states. Based on the 2020 U.S. Census Data, New York County has a population of 1.7 million people, with a total of 8.3 million people in the New York City area, Philadelphia has 1.6 million, Bucks County has about 647,000, Chester County has about 535,000, Passaic County has about 525,000, and Somerset has about 345,000 (12). Between September 1st and September 2nd, Philadelphia, Pennsylvania experienced a decrease in Overall Total Daily Visits to Places of Interest (POIs) of approximately 10,000 Total Recorded Visits (as shown in Graph A). As depicted by Graph F.1, New York City, New York experienced an even greater decrease of approximately 25,000 visits during the storm. While both urban areas showed a great decrease in total visits, the number of overall visits remained high when compared to suburban and rural communities with significantly smaller populations. In suburban Passaic County, New Jersey, Overall Total Daily POI Visits decreased by approximately 3,000, from roughly 35,000 to about 32,000 visits between Wednesday and Thursday (Graph D). Somerset County, New Jersey, experienced an even greater reduction of approximately 6,000 visits during that timeframe, from under 23,000 to about 17,000 visits (Graph E). Bucks County, Pennsylvania, which experienced the brunt of the storm on Wednesday, September 1st saw a drop of about 75 (approximately 250 to 175) Total Visits from the day before (Graph B). Visits remained low on Thursday with only a slight increase. Finally, Chester, Pennsylvania, with a population 112,000 less than Bucks County, experienced approximately 100 less visits during the storm, again with a slight increase on Thursday (Graph C.1).

In the days following Hurricane Ida, all six counties experienced great increases in Overall Total Daily Visits, with all counties greatly surpassing the number of Total Daily Visits they had prior to the storm.

Data collected from Chester County, Pennsylvania shows a 3-Week Comparison of Average Wednesday Visitors by Business Type, including Education, Food, Government, Healthcare, Religious, Retail, and Other types of businesses (Graph C.2). During the flood week, average Wednesday visits to Education and Healthcare businesses were higher than both pre- and post-flood weeks, whereas visits to Food and Religious businesses decreased compared to pre- and post-flood weeks. Education experienced a 33.3% increase in Average Visitors during the flood week, and Healthcare experienced a 50.0% increase. Food businesses experienced an 18.7% decrease in visitors, while Religious institutions experienced a 22.4% decrease in Average Visitors.

3.b) Data collected from all six counties was then analyzed together to reveal any trends, patterns, or anomalies that occurred in collection. Analyzing the Comparative Impact of Hurricane Ida Across Six Counties showed that Somerset County experienced the greatest drop in Normalized Daily Visits with a Mean of 1.0, dropping to roughly 0.75 during the Hurricane Ida Period (Graph G.1). Across all six counties, the Most Negatively Impacted Industry-County Combination During Hurricane Ida were the Administrative and Support and Waste Management Services in New York County, with a 29.2% decrease in visits. Information and Real Estate Rental and Leasing Industries in Somerset County were close behind with a 25.3% decrease and a 23.3% decrease respectively (Graph G.2).

Data was also analyzed to predict when visitation and travel would return to pre-Ida values. The Predicted Recovery Trajectories by Region predicts the number of days it will take for these regions to recover from damage, flood or otherwise, caused by Hurricane Ida (Graph G.3). All six counties show recovery after fourteen days after the event occurred. While the Urban Centers and Northern NJ Counties exhibit a similar trajectory, the more rural PA Suburban Counties show a slower recovery, just slightly surpassing the Pre-Ida value of 1.0 at the fourteen-day mark. Overall, the Urban Centers of Philadelphia and New York City show the greatest amount of recovery in the two weeks after Hurricane Ida.

4. Discussion

Results show that visitation and travel trends were greatly disrupted by the remnants of Hurricane Ida as it passed over six counties in New York, New Jersey, and Pennsylvania. In New York City and Philadelphia, it is important to recognize why visitation and travel patterns are still incredibly high during the severe weather event, outside of their significantly larger populations. This hurricane occurred at the end of August into the beginning

of September. New York and Philadelphia, as major tourist cities, are top vacation spots for millions of people, not just in the United States, but around the entire world. Families may be seeking their final vacation of the year, especially as the summer ends and school starts again. These high levels of tourism greatly contribute to the large number of individuals still traveling and visiting businesses during the hurricane. New York City likely experiences the greatest decrease in visitors, not just because it has the largest population, at roughly 8.3 million people in the area, but also because of the flood damage to public transportation, specifically the subway. Individuals in cities such as Philadelphia and New York rely heavily on public transportation, so if it is severely damaged or inoperable due to flooding, significantly less individuals will be able to travel.

In rural and suburban areas with smaller populations, individuals rely more on personal vehicles, such as cars and trucks. As a result, the decrease in total visits may not be as drastic because individuals are free to travel unless the county closes the roads. The smaller populations in these areas also mean that there are generally fewer people traveling in the area, as shown by the difference in total visit values.

In the days after the storm, all six counties showed a significant increase in travel and visitation. This may be due to individuals finally getting the opportunity to leave the house after a few days of severe weather, whether it be for work, food, supplies, to meet with friends, or to simply leave the house. It is also important to note that the days following Hurricane Ida's storm were weekend days, Friday, Saturday, and Sunday, which regularly experience the most travel. However, in most cases we researched, visitation was greater during this flood weekend than during the weekends of the pre- and post-flood weeks. This highlights the importance of coupling mobility data with contextual datasets, such as utility restoration, transit availability, or claims activity, in order to differentiate between adaptive recovery and reactive coping behaviors. Essentially, it is important to consider other possible motives for increased or decreased travel and mobility in a region. This includes weekends or weekdays, holidays, local events, seasonal activity, etc., as all of these factors can greatly impact mobility on any given day. The weekend immediately after the flood event could have experienced this increase in travel due to a variety of those factors, such as the end of summer for students or because individuals spent too much time at home due to the flood conditions.

In Chester County, Philadelphia, there was a 33.3% increase in travel to Education facilities and a 50.0% increase to Healthcare businesses during the flood week. The increase in Education travel and visitation could be due to the school year starting in this county. For the Healthcare business increase, it is possible that individuals in Chester County experienced some storm-related injuries that required medical aid, as it decreased 16.7% post-flood week. A similar trend in Healthcare visitation occurred in New York City, as visits to both Health and Personal Care Stores and General and Surgical Hospitals increased by approximately 400 visits (Figure F.2).

For Predicted Recovery Trajectories by Region, it is important to consider the possible reasons behind why more rural PA Suburban Counties experience a slower recovery compared to Urban Centers and the Northern NJ Counties. The slower recovery trajectories observed in Bucks and Chester Counties raise critical questions about the unequal pace of post-disaster recovery across community types. These areas, with lower population densities and fewer healthcare or public infrastructure nodes, may lack the institutional capacity or political visibility to attract swift emergency responses. Our analysis reflects the unequal allocation of recovery resources, potentially compounding pre-existing disparities in mobility access and service provision. Understanding these disparities through mobility data can help planners proactively allocate surge resources and develop tiered recovery benchmarks that are sensitive to community-scale resilience capacities.

These findings align with prior research emphasizing how social and infrastructural disparities shape differential disaster recovery trajectories (8). In our analysis, this pattern is reflected in the flatter post-disruption mobility curves observed in Bucks and Chester Counties, which lack the rapid rebound seen in more urbanized counties.

Throughout Graphs A, B, D, and F, multiple significant visitation decreases were identified in the weeks prior to and after Hurricane Ida. While in-depth analyses of these decreases have not yet been conducted, it is possible these decreases were caused by storm and hurricane events during that time. Tropical Storm Fred, which occurred from August 11th through the 17th, passed over all six researched counties (14). Similarly, based on the location of Tropical Storm Mindy that occurred from September 8th to the 9th, as well as Hurricane Nicholas that occurred from September 12th to the 15th, it is possible that remnants of those storms impacted travel in the six counties in the following days, causing the decreases in travel identified on the graph, though further research must be conducted to prove or disprove this possibility (14).

There are a few limitations in this study, beginning with multiple socioeconomic factors. Income, occupation, community, and health resources available may have impacted mobility for individuals in the six counties. Further research should be conducted to determine how these factors affect individuals' ability to travel, seek shelter, and remain safe during severe weather events. For example, in New York City, thirteen people were killed in basement

apartments during the Ida floods. The victims were low-income, minority, and immigrant individuals, groups that are often the most at risk during severe weather events such as Hurricane Ida (13). This research should be expanded to include analysis of various socioeconomic factors to determine the impact they have on mobility during flood events. Additionally, this research is geographically limited, focusing on only six counties across three states. Furthermore, the researched areas did not face the full force of Hurricane Ida, experiencing only storm remnants in the days after the hurricane made landfall as a Category 4. There are more urban, rural, and suburban locations this research could be expanded to for further analysis of how different regions and landscapes impact mobility during flood events.

5. Conclusion

The mobility shifts observed in this research reveal the differing responses on the ground, which may have been influenced by factors such as dependence on public transit in an urban setting and heightened demand for certain services over others during and after the flood. While these findings allow for several insights derived from large-scale mobility data analysis, the six-county set serves as a first step. It is important to note that this study focused on the downstream flooding effects in the Northeast; mobility disruptions and recovery trajectories could differ significantly in regions that experienced the storm's primary Category 4 impact. A possible subject for continued study could include extending the scope of the analysis to incorporate a larger set of affected areas, with the addition of more socio-economic data and flood-severity data to allow for a more detailed description of vulnerabilities and finer-scale articulation of resilience strategies. Further directions of extension toward more sophisticated approaches to time-series analyses would also grant greater insight into the various time scales of disruption and recovery.

In essence, this study shows how digital footprint data could be used as a tool for a rapid evaluation of actual mobility outcomes due to severe weather disasters. Understandably, such impacts differ among varied community types and service sectors, for which enhanced and targeted preparedness, emergency response, and equitable recovery have been the order of the day amidst increased climate adversities.

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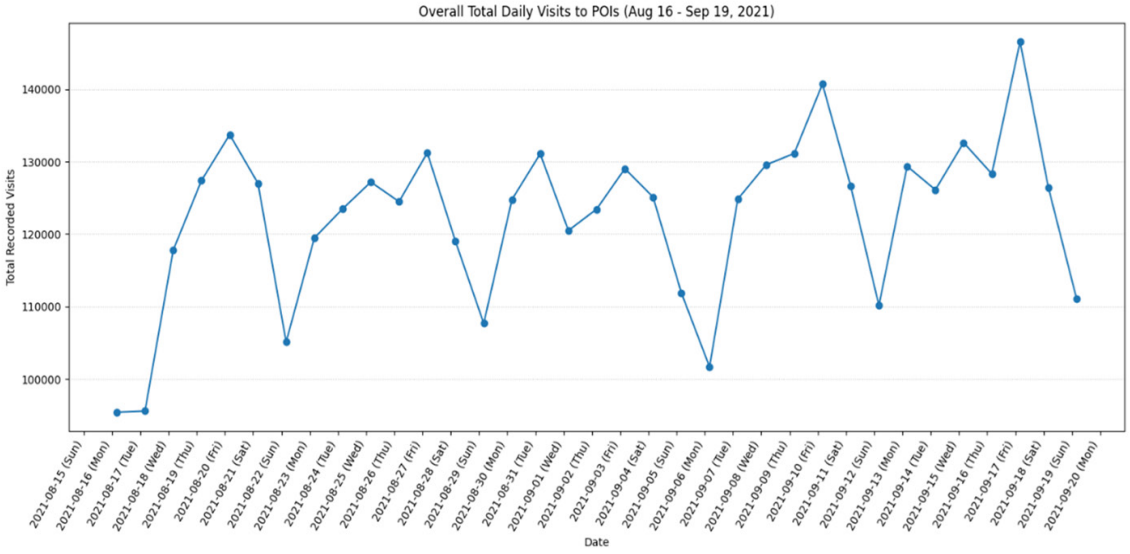
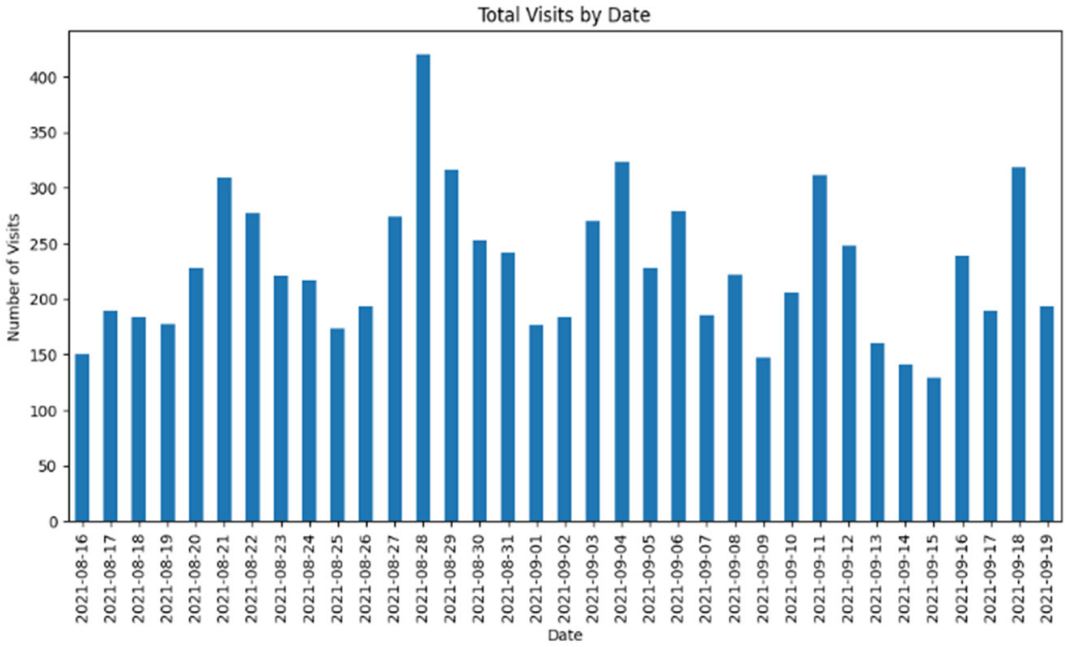
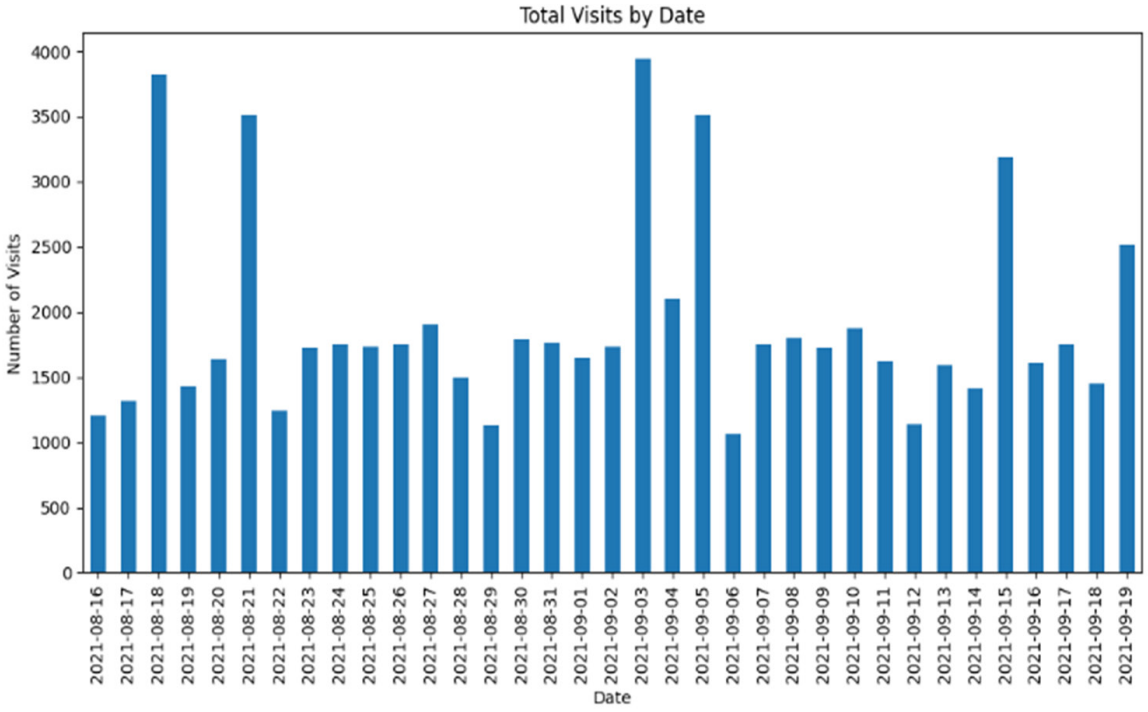
APPENDIX



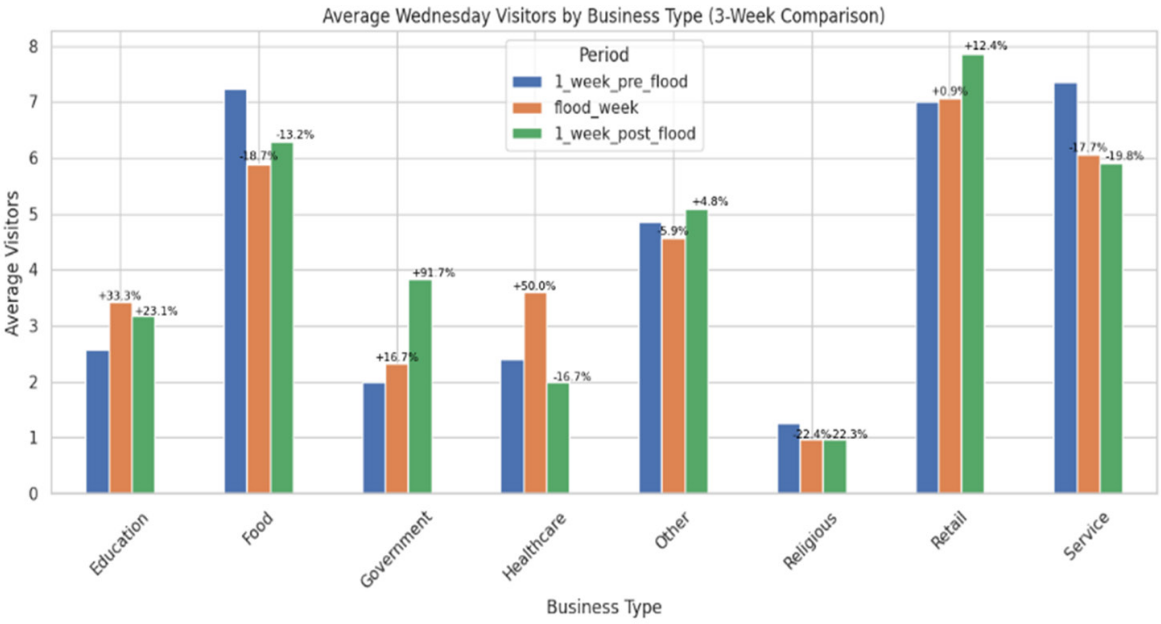
Graph A. ***Philadelphia, PA.***



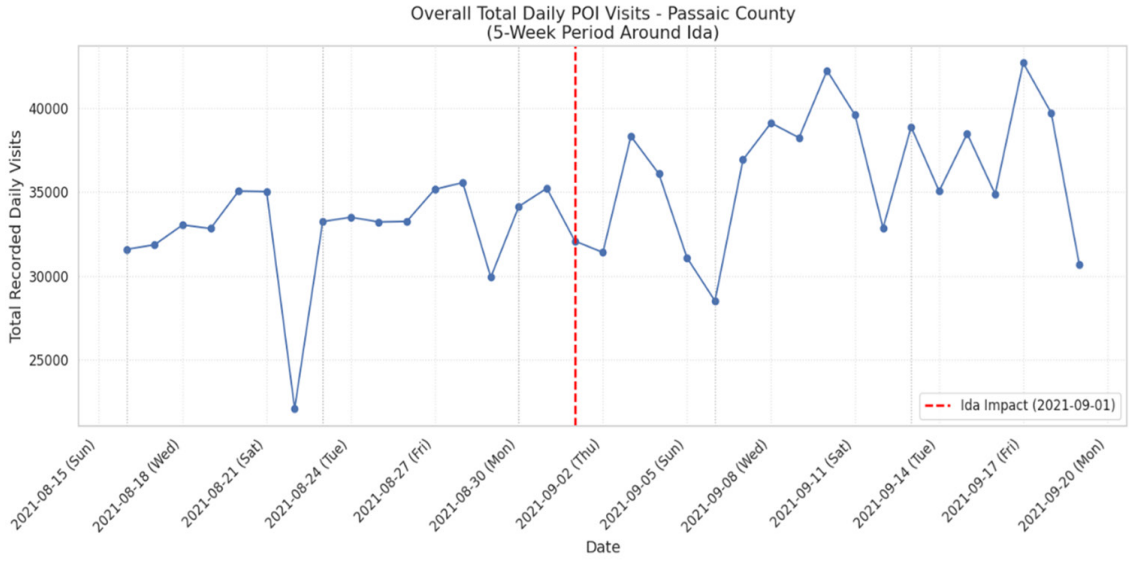
Graph B. ***Bucks County, PA.***



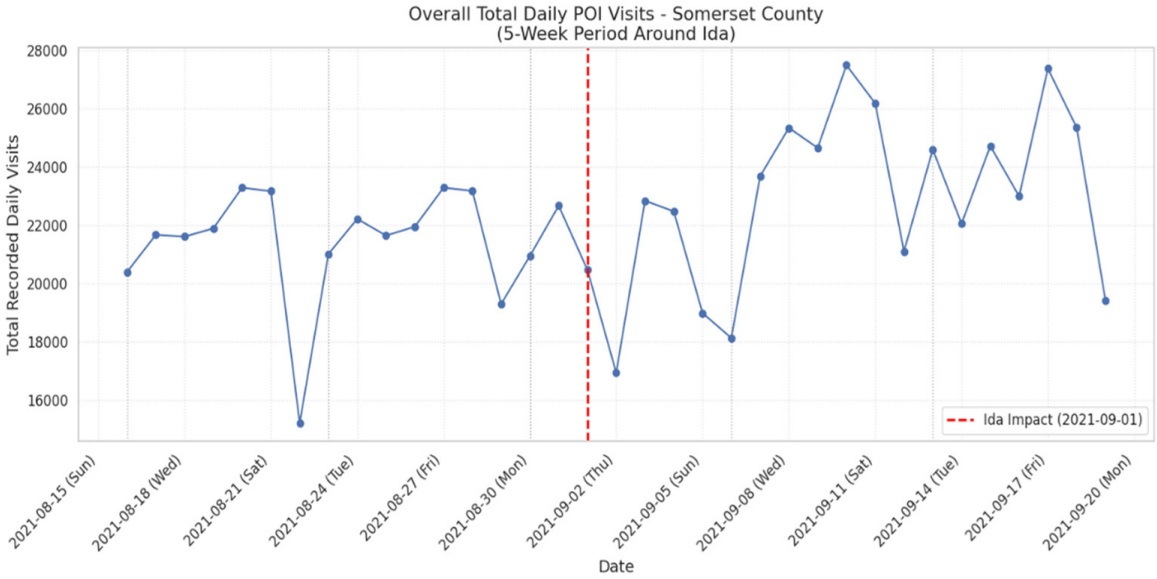
Graph C.1. ***Chester County, PA.***



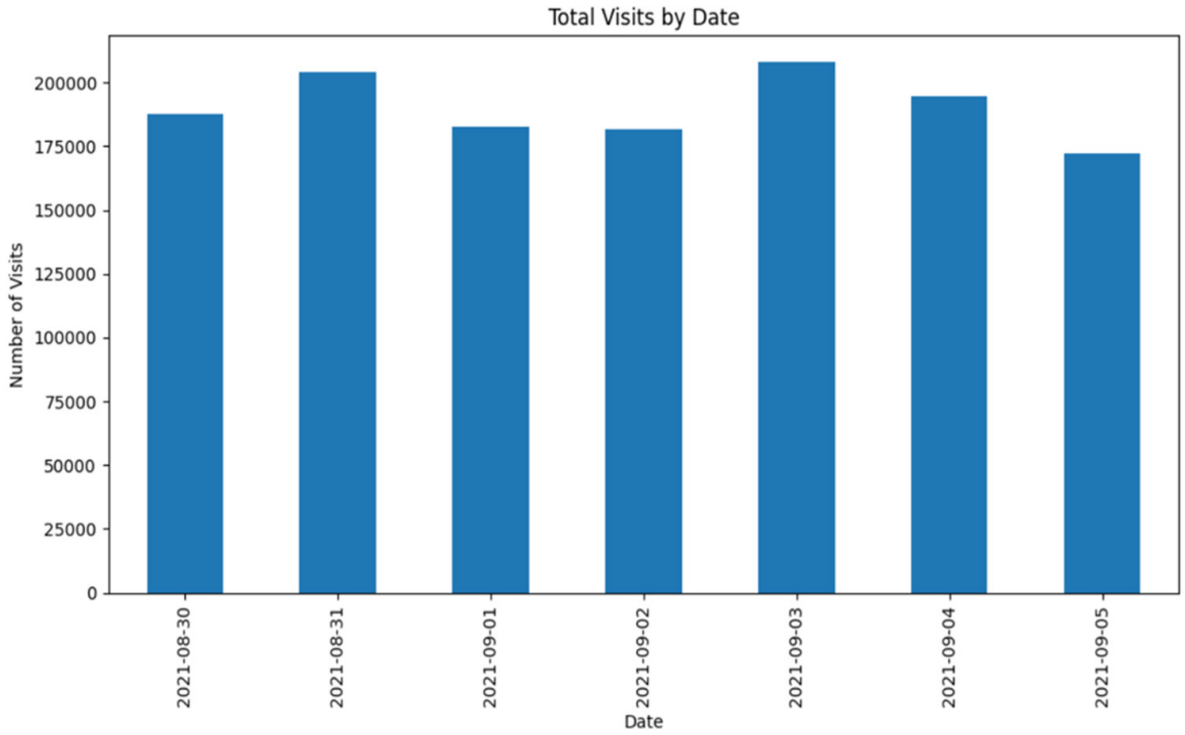
Graph C.2



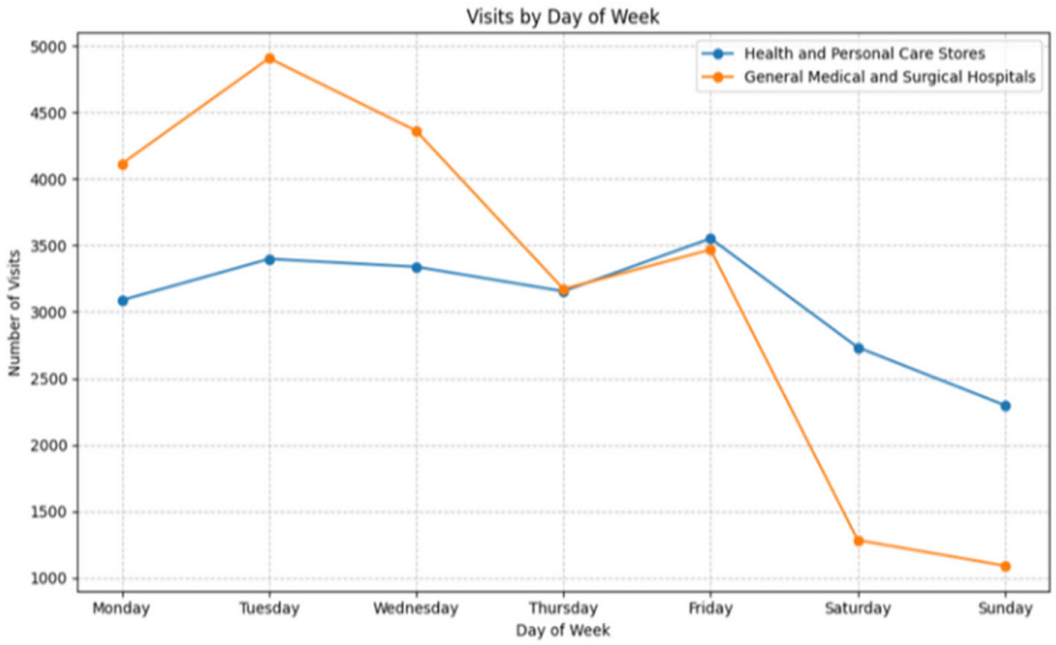
Graph D. ***Passaic County, NJ.***



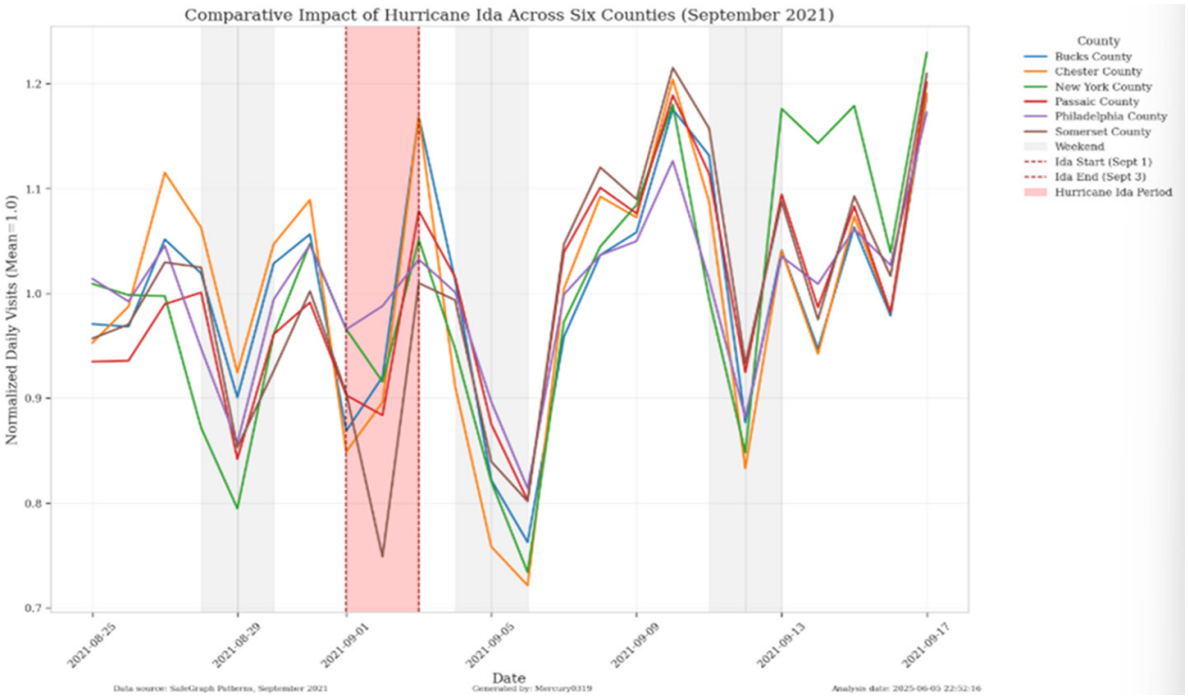
Graph E. ***Somerset County, NJ.***



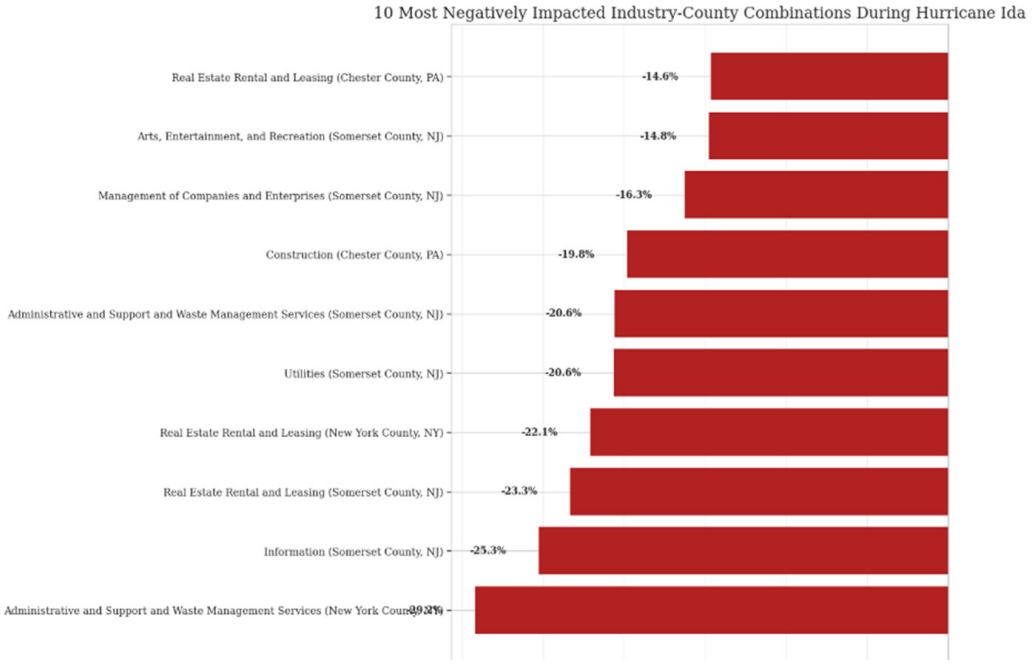
Graph F.1. ***New York City, NY.***



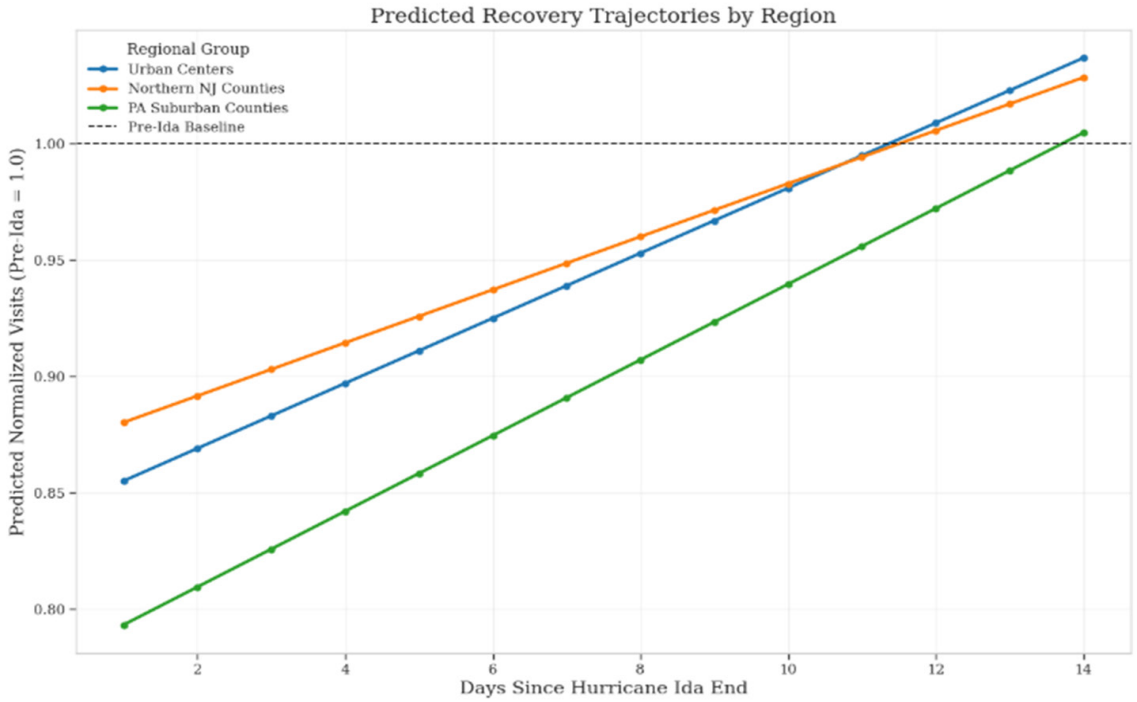
Graph F.2.



Graph G.1.



Graph G.2.


Predicted Recovery Trajectories by Region
Regional Group
Urban Centers
Northern NJ Counties
PA Suburban Counties
Pre-Ida Baseline
Predicted Normalized Visits (Pre-Ida = 1.0)
1.00
0.95
0.90
0.85
0.80
2
4
6
8
10
12
14
Days Since Hurricane Ida End

Graph G.3.

Author
Alex Rodriguez

Alex Rodriguez, Villanova University Class of 2028, is pursuing a Bachelor of Science in Civil Engineering with an honors degree. This is his first time conducting research at a collegiate level. Through both the Match and VURF Research Program for first-year students, he began his research project with Dr. Chenfeng Xiong's team in the Department of Civil and Environmental Engineering, focusing on the mobility impacts of Hurricane Ida's flooding through statistical analysis and data-driven methods. Originally from New Jersey, he is especially interested in how infrastructure and social equity intersect in disaster recovery and hopes to continue pursuing research that addresses these critical challenges.

Mentor
Lele Zhang

Lele Zhang is a member of NovaMobility. Her research focuses on human mobility, transportation resilience, and the impacts of extreme weather events on urban systems. She applies causal effect analysis and advanced Bayesian approaches to evaluate transit ridership, flood mobility, and socioeconomic disparities in climate adaptation. She is also interested in AI-driven modeling to advance disaster resilience research. Her broader academic goal is to inform climate adaptation and equitable transportation planning in cities worldwide.

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Juliet Cimaglia is a second-year student at Villanova University pursuing a Bachelor of Science in Mechanical Engineering with an honors degree. She worked on this project as part of the Freshman Match Research Program through the Spring and Summer 2025. This was her first time doing college-level research. This fall, Juliet started a biomedical engineering research project focused on CPR and Ventilation Modeling through the Mechanical Engineering Department's Sophomore Research Scholars Program.

Mentor
Dr. Chenfeng Xiong

Dr. Chenfeng Xiong is an Assistant Professor in the Department of Civil and Environmental Engineering at Villanova University. He teaches transportation engineering and planning, and leads research aimed at understanding the fundamentals of human mobility and transportation systems—focusing on traveler behavior, mobility patterns, safety, health impacts, and transportation economics. He has published over 80 scientific research articles in these areas. His research has been funded by National Institutes of Health, National Science Foundation, and US Department of Transportation.

Author
Jay Gorgas

Jay Gorgas is a second-year student at Villanova University. He is pursuing a Bachelor of Science in Civil Engineering with a minor in Sustainable Engineering. He worked on this project as a Spring 2025 First Year Match participant, and this was his first time conducting research at the collegiate level. On campus, Jay is an active member of Villanova Club Tennis, American Society of Civil Engineers (ASCE), and the National Society of Professional Engineers (NSPE). He is looking forward to participating in additional research opportunities in the future.