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Co-resilience Assessment of Hurricane-induced Power Grid and Roadway Network Disruptions: A Case Study in Florida with a Focus on Critical Facilities

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Abstract — Florida's emergency relief operations were significantly affected by recent hurricanes such as Hermine and Irma that caused massive roadway and power system distributions. During these recent devastating hurricanes, the problems associated with providing accessibility and safety became even more challenging, especially for those vulnerable communities and disadvantaged segments of the society, such as aging populations were considered – that is, those who need and benefit from the emergency services the most. This complexity is magnified in states like Florida, considering the diverse physical, cognitive, economic and demographic variation of its population. As such, with a major focus on real-life data on roadway closures and power outages for the Hurricane Hermine, combined resilience (co-resilience) of emergency response facilities in the City of Tallahassee, the capital of Florida, was extensively studied based on the (a) temporal reconstruction of the reported power outages and roadway closures, and (b) development of co-resilience metrics to identify and visually map the most affected power system feeders and transportation network locations. Results show those regions with reduced emergency response facility accessibility, and those power lines and roadways under a disruption risk after Hermine hit Tallahassee.

Keywords— Emergency Response, Co-Resilience, Power Outages, Roadway Closures

I. INTRODUCTION

Recent hurricanes, namely Hermine and Irma, exposed weaknesses in cities' preparedness for and response to these emergency situations. Unfortunately, threats posed by hurricanes may likely be even worse in the future due to climate change effects, aging infrastructure, and rapid population growth. The weaknesses largely resulted from the inability of the affected city components (i.e., roadways and power lines) to effectively cope with random and dynamic changes. Therefore, providing optimal swift service restoration solutions based on lessons learned are critical for governments, utilities and emergency responders to evaluate the service availability and resilience of existing roadways, power networks, and other services simultaneously. Such shortfalls have translated into the resilience deficiencies while amplifying vulnerabilities and exposing gaps in planning and response.

For example, Florida's emergency relief operations were significantly affected by Irma, with the 80 to 100 mph sustained winds that toppled trees and utility poles, taking power, cable, and phone lines with them. Power restoration crews were also significantly slowed down by the closure or loss of roadway sections because of debris, such as fallen trees, particularly in the cases in which the removal of the trees was under the jurisdiction of public works rather than power restoration crews. Such lack of coordination was one of the main reasons for delays in handling the power outage-related problems, which were especially critical for facilities such as police stations, fire stations and hospitals. This is especially critical for the sake of vulnerable communities and disadvantaged segments of the society, such as aging populations who need and benefit from the emergency services the most. This complexity is magnified in states like Florida, considering the diverse physical, cognitive, economic and demographic variation of its population.

Resilience in general is defined as the ability to withstand stress measures without suffering operational compromise. This definition also includes the ability to withstand operating excursions outside the normal operating envelope with a tendency to return to operations within the normal envelope. The ability of city systems to withstand such disaster-related disruptions and quickly recover from them is defined as multi-dimensional city co-resilience, a system property, which ensures flexibility and adaptability to cope with the unexpected disturbances [1]. A resilient emergency response plan, therefore should include strategies to evaluate the conditions of existing roadway and power networks during and in the aftermath of disasters such as hurricanes using historical data in order to achieve co-resilience and identify the critical locations. Focusing on this co-resilience-based analysis is especially critical since providing necessary aid timely to hurricane victims, especially those that are the most vulnerable, can alleviate possible adverse consequences of hurricanes.

Previous research shows that transportation accessibility has been a special interest, especially given the advances in computational power that has enabled the analysis of more computationally complex problems. Numerous studies have focused on the accessibility of critical facilities such as multimodal facilities [2], and shelters [3]. There have also been some studies characterizing the interdependencies between transportation and electricity networks [4, 5], and indicating the need for developing such methodologies utilizing big data in the smart city context [6]. These studies mostly take advantage of Geographical Information Systems (GIS)-based tools to perform accessibility analysis. Investigating the structural properties of networks in the context of resilience and robustness is also significant in order to understand the complex dynamics of city systems. In the literature, there are a variety of methods that discuss the reliability, resilience, vulnerability and failure process of power and transportation networks [7-11]. Note that power systems and transportation networks are facing a wide variety of disturbances with different probability of occurrences due to hurricanes. To enhance the resilience of any system, it is necessary to consider how disasters such as hurricanes may disrupt the infrastructure [12], and how countermeasures can be employed to deliver real-time relief and resilient emergency response [13-17].

However, to the authors' knowledge, there has not been a study that focused on the co-resilience (power and transportation network resilience together) through investigating the emergency facility accessibility based on real-life disaster data. In this study, with a focus on actual data from the Hurricane Hermine 2016, accessibility and power resilience of emergency response facilities such as police stations, fire stations and hospitals in Tallahassee, the capital of Florida, were extensively studied using real-life data on roadway closures and power outages. This was achieved by the (a) temporal reconstruction of the reported power outages and roadway closures on the Tallahassee power and roadway networks in the one-week window after Hermine hit Tallahassee, and (b) development of resilience metrics to identify and visually map the most affected power system feeders and transportation network locations. In order to assess the impact of the hurricane on the city, these metrics were based on focusing on critical vulnerable system components. Based on the governmental recommendations [18-21], critical facilities such as hospitals are also taken into account in the analysis. Since the system resilience is a poly-dimensional dependence property as pointed out in [1], the proposed model not only focuses on the city power grid and roadways but also comprehends more dimensions such as spatial distribution of critical facilities and emergency crew restoration strategies.

II. METHODOLOGY

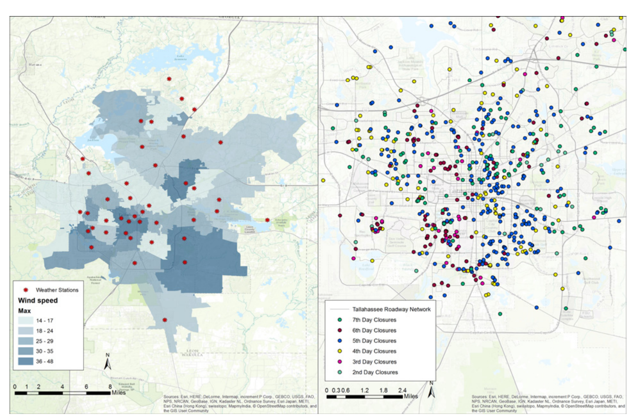
This section presents the methodology for the co-resilience assessment. The Co-Resilience is a novel concept that measures integrated electricity and transportation network resilience to model simultaneous interaction between city infrastructure networks. In this paper, the co-resilience of power lines and roadways has been studied with a specific focus on critical emergency facilities.

A. Study Area, Hurricane Hermine and Data

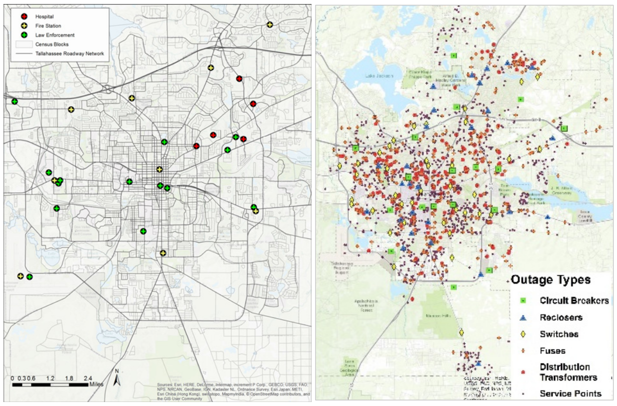
The City of Tallahassee, the capital of Florida, being the most populated city in the Leon County, hosts 286,272 people, and is home to two major universities and a community college. The urbanized area of Tallahassee has a population of 190,894 according to the US Census estimate [22]. The City of Tallahassee is a full service municipality providing essential services to the region: electric, gas, water solid waste, sewer, public works, airport, mass transit, etc.

Tallahassee was hit by Hurricane Hermine in September, 2016. Hermine provoked disruptions in all services in Tallahassee from 10:00 PM of September 1st, 2016 to 4:00 AM of the next day September 2nd, affecting thousands of customers [23]. Maximum speeds reached during Hurricane Hermine varied for different parts of the city (Fig. 1-a). These high wind speeds resulted in fallen trees and roadway disruptions in Leon County (Fig. 1-a). Hurricane Hermine also provoked power system disruptions in Tallahassee from 10:00 AM on September 1st, 2016 to 4:00 AM on the following day, September 2nd, affecting 60,928 customers.

Data resources provided by the city include the power outages, roadway closures, and the whole power and roadway networks. Power outages information included the outage detection time, outage restoration time, outage device type, and number of affected customers per outage. During Hurricane Hermine, 776 roadway closures were reported due to fallen trees in a one-week window (Fig. 1-b). Note that, 7th day closures shown in Fig. 2-b do not correspond to a closure that occurred on 7th day, but corresponds to a closure that exists until 7th day. In case of an emergency, police, fire and hospital response teams are dispatched to locations of the emergency. In Tallahassee, five hospitals, thirteen fire stations, and fourteen police stations are ready to serve the public (Fig. 1-c).



(a) (b)



(c) (d)

Fig. 1 Study area (a) Wind speeds at U.S. Census blocks during Hermine (b) Roadway closures (c) U.S. Census blocks and emergency response facilities (d) Power network disruptions

B. Development of Co-Resilience Metrics

Utilizing the data mentioned in the section A, a detailed methodology has been developed to evaluate the impact of the Hermine-induced roadway closures and power outages in the City of Tallahassee and its corresponding emergency facilities. As such, following metrics have been developed:

B.1. Outage Duration Time

Outage Duration Time (T_d) is the difference between the outage detection time and the outage restoration completion time. It should be considered that detection time depends on a ping operation, which is effective only if there is a functioning connection between the customers or substations, and the substation supplying electrical energy (1):

$$T_d = T_r - T_0, \qquad \forall outage \qquad (1)$$

where *d*=duration, *r*=restoration and *o*=outage detection.

B.2. Outage Temporal Density

Outage Temporal Density (D_i) was calculated as the number of outages per each half hour, starting from time zero (in our case, the time Hermine hit Tallahassee: 10:00 PM on September 1st, 2016) as follows (2):

$$D_i = O(30i) - O(30(i-1)), \qquad \forall i \qquad (2)$$

where *i*=interval number, *O*=number of outages from time zero to expressed bracketed time in minutes.

B.3. Roadway Closure Duration Time

Roadway Closure Duration Time (RT_d) is the difference between the time the roadway closure detection time and the roadway cleaning time (3):

$$RT_d = RT_r - RT_0, \qquad \forall closure \qquad (3)$$

where *d*=duration, *r*=roadway clearing and *o*=roadway closure detection.

B.4. Roadway Closure Temporal Density

Roadway Closure Temporal Density (RD_i) was calculated as the number of roadway closures per each half hour, starting from time zero (the time Hermine hit Tallahassee: 10:00 PM on September 1st, 2016) as shown in (4):

$$RD_i = RO(30i) - RO(30(i-1)), \qquad \forall i \qquad (4)$$

where *i*=interval number, *RO*=number of roadway closures from time zero to expressed bracketed time in minutes.

B.5. Lack of Resilience

Lack of Resilience (RL_{out}) is represented by outages affecting a large number of customers for a long duration (5). It was calculated per each outage as the product of the number of customers and the outage duration that accordingly lost power supply, normalized with respect to the maximum product result among all outages as follows:

$$RL_{out} = \log_{10}\left(\frac{C_{out} * T_d}{max\{C_{out}, T_d\}}\right), \forall outage \qquad (5)$$

where *out*=outage, *C*=number of customers. In addition, the logarithm function has been used to facilitate the analysis to visually expand the small resilience lack values.

B.6. Feeder Vulnerability

Feeder Vulnerability (FV_f) measures outages recorded per feeder when it faces hazards such as hurricanes [51, 52]. In this paper, FV_f is calculated as shown in Equation (1) below:

$$FV_f = \frac{avg(C_{out} * T_{d,f}) * O_f}{max\{avg(C_{out} * T_{d,f}) * O_f\}}, \forall f \qquad (6)$$

where *f* = feeder, O_f= outages per feeder f.

B.7. Feeder Prioritizing

The feeder priority factor (FP) is the key to ensure a resilient power system. This paper utilizes the available priority benchmarks for critical facilities given in the literature [24-26] to develop the prioritization presented in Table 1.

TABLE I. Group and Facility Prioritization

Group	Group priority (w_g)	Facilities number	Facility priority (*FacP*)
Hospital 1, 770 beds	0.193	1	0.193
Hospital 2, 198 beds	0.0495	1	0.0495
Hospital 3, 76 beds	0.0190	1	0.0190
Hospital 4, 46 beds	0.0115	1	0.0115
Hospital 5, 29 beds	0.00726	1	0.00726
Total hospitals	0.28	5	Varies as shown
Surgical centers	0.08	13	0.00615
Nursing homes + hospices	0.024	13 + 1	0.00171
Assisted living facilities	0.016	12	0.00133
Total health care	0.4	44	Varies as shown
Law enforcement	0.15	20	0.0075
Fire stations	0.15	13	0.0115
Shelters	0.12	38	0.00316
Correctional facilities	0.08	5	0.0160
Total prioritized	**0.9**	**120**	**0.9**
Unprioritized	**0.1**	**All the remainder**	**Group fraction**

Although there are no general restricting rules about the load prioritization, the expert knowledge from the City of Tallahassee and other governmental institutions was utilized in categorizing critical facilities. Therefore, as shown in Table I, the more critical a facility group is, the higher its priority, and total priority sums up to 1. In addition, hospital priorities have been calculated as a fraction of the whole hospital group priority, proportional to the bed capacity of each hospital. Each unprioritized electrical customer, such as residential or commercial entity, has been assigned the same priority, which is a value of 0.1. After the priority assignment, the feeders providing electricity to each prioritized customer have been detected, and were assigned an equal fraction of prioritized customer priority as follows in (2):

$$FP_f = \sum_{l=1}^{L} \frac{FacP_l}{F_l}, \forall f \quad (7)$$

where L=number of facilities served by feeder f, F_l=fraction of feeders serving to prioritized facility l. This metric succeeds in feeder prioritization through assessing how critical a feeder is for high priority facilities. If a feeder feeds a certain number of critical facilities, and these facilities are fed by a small number of feeders, then this feeder has a high priority since its' failure can lead to disruption in the operation of the facilities. Note that since the distribution of unprioritized customers among feeders are not available in the data, only prioritized groups have contributed to feeder priority calculation, so feeders' priorities sum is equal to 0.9. Those feeders which do not feed any prioritized facility have been named unprioritized.

B.8. Power Resilience Need

After measuring the resilience using the proposed Outage Duration, Outages Temporal Density, Lack of Resilience, and Feeder Vulnerability indices, the building priorities were calculated. Then, the power system Resilience Need (*RN*) metric for each electricity distribution feeder, *f*, has been proposed as a spatiotemporal factor to highlight which highly prioritized feeders have been most vulnerable to a hurricane. Equation 3 provides the proposed *RN* factor calculated as the normalized product of priority and feeder vulnerability:

$$RN_f = \frac{FP_f * FV_f}{max\{FP_f, FV_f\}}, \forall f \quad (8)$$

The number of customers, the time of outage, the priority of customers, the restoration time and the number of time that customers experience outage during a disaster are all embedded into the *RN* factor for each feeder. The summation of all *RN* values presents the overall need for power resilience in a city.

B.9. Transportation Vulnerability

Transportation vulnerability (TV_k) metric for a facility k was defined as the product of facility priority (*FacP*) and the number of roadway closures within 2 minutes in terms of accessibility from the facility. Total number of Roadway Closure Temporal Density (RD_i) of all intervals i for a specific facility k gives us the total number of roadway closures. Using this number, the TV metric provides us the vulnerability of the facility, by proportioning its priority to the roadway closures in the context of accessibility. For instance, the more critical a facility is, the higher the priority is. Moreover, if that facility has more roadway closures in the vicinity, that facility is highly vulnerable. Especially during hurricanes, when there is a need to dispatch emergency vehicles, efficient response becomes a critical issue. This metric can also provide an understanding on the accessibility of vulnerable facilities with a high priority:

$$TV_k = FacP_k - \sum RD_i, \quad \forall k \quad (9)$$

II. CRITICAL FACILITIES AND POWER INFRASTRUCTURE ASSESSMENT

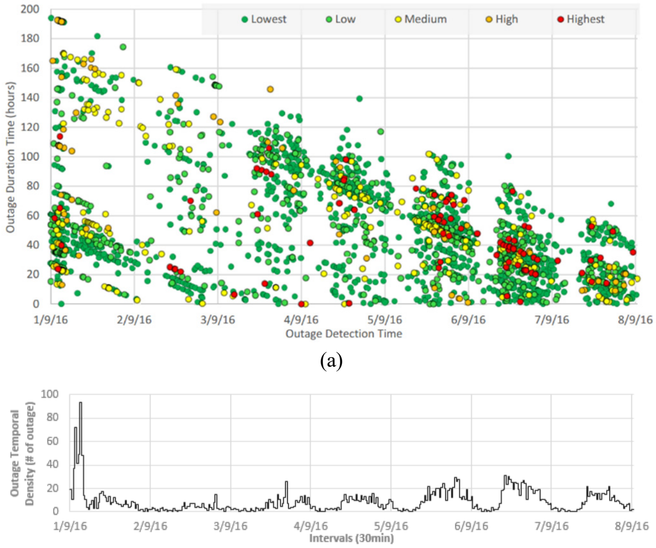
Starting with the temporal analysis, Fig. 2 captions and color codes are structured as follows: y axis show the number of hours and the x axis show the dates. The time starts at 10:00 PM on September 1st, 2016, when Hermine first hit Tallahassee, and the time is formatted as dd/mm/yy per each 24-hour interval. So, each date label corresponds to the time of 10:00 PM. Hermine left the city at around 4:00 AM on September 2nd. FIGURE 2a provides information on how many hours each outage lasted, and when it was detected. There is a clear linear pattern suggesting that the later an outage has been detected by a ping operation, the less time it took to the city to restore it. This shows that emergency management worked methodically with respect to the outage duration. Colors also show that outages that belong to feeders with highest priority (red) have an average outage duration, which is consistently lower than the maximum. This indicates that feeders being prioritized the most in this paper have been taken care of by the city more efficiently than other feeders.

Observing Fig. 2a, it is notable that there are high density outage time zones. Therefore, outage temporal densities have been calculated, to determine the number of detected outages during each half an hour period (Fig. 2b). The highest number of outages is recorded when Hermine was still active in Tallahassee; however, from September 4th to the 8th, there are day by day growing peaks recorded during day time, possible confirmation of the fact that the utility has not been working during night with respect to the ping operations.

For a comprehensive analysis, the location of damaged components and their spatial distribution are also crucial. Therefore, the proposed mathematical metrics have also been mapped using the ArcGIS software. Fig. 3a depicts the location of the most prioritized feeders based on the most prioritized customers, such as hospitals, fire and police stations. Fig. 3b shows the most vulnerable feeders during Hurricane Hermine. Finally, Fig. 3c shows those highly prioritized feeders, which have been most vulnerable to Hermine, especially those that are shown in yellow and light green. In other words, Fig. 3c shows those areas where the power system resilience need during the hurricane did not comply with the critical facility feeder priorities proposed in this paper. Therefore, they are possible areas that the city can identify, and consider for future resilience-oriented investments.

III. CRITICAL FACILITIES AND TRANSPORTATION INFRASTRUCTURE ASSESSMENT

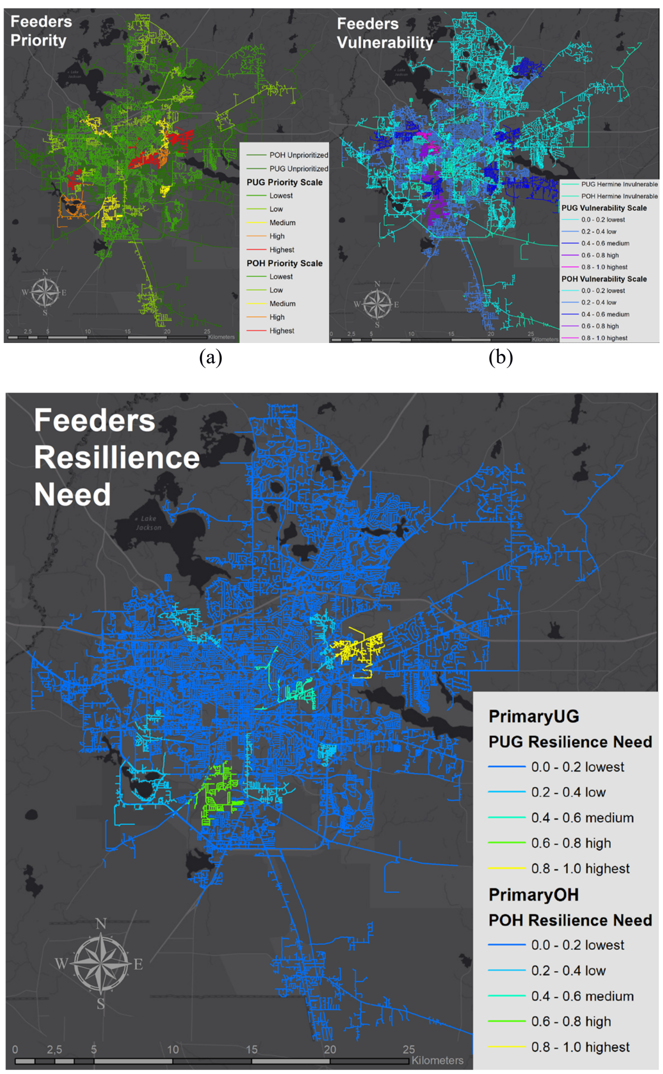
Fig. 4a provides information on when each roadway closure was detected, and how many hours it lasted. There is a slightly decreasing pattern showing that the later a roadway closure has been detected, the less time it took the public works crews to clear the roadway. Note that some of the roadways could be out of reach due to consecutive roadway closures. After first couple of days, roadway closure duration time dropped to the levels of 20-40 hours. At the end of the one-week window, less than 20 hours duration times were observed. To identify if temporal clusters existed, roadway closure temporal density measures were calculated to determine the number of detected roadway closures during each half an hour period. (Fig. 4b). Fig. 4b shows that highest number of roadway closures were observed on Day 3, one day after the Hermine's hit on Tallahassee.



(a)

(b)

Fig. 2 (a) Outage duration and outage detection; colored by feeder priority scale, (b) Outage temporal density, detection time



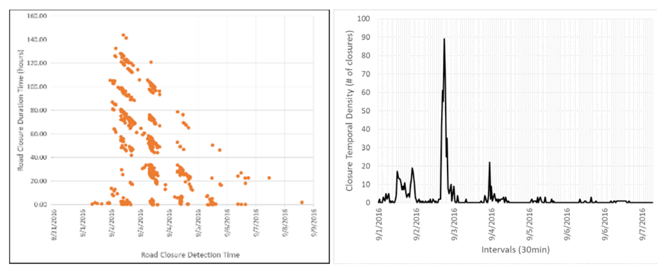
(a)

(b)

(c)

Fig. 3 (a) Feeders priority; red (highest) - dark green (lowest), (b) Feeders Vulnerability; pink (highest) - light blue (lowest), (c) Power resilience need; yellow (highest) - dark blue (lowest)

Transportation vulnerability analysis is conducted for three hospitals, one police station and one fire station. Roadway closures within 2 minutes of travel time were obtained and displayed in maps using ArcGIS (Fig. 5). Following that, facility priority values were multiplied with the roadway closure number to obtain the proposed transportation vulnerability (TV) metric. Results show that Hospital 1, which is the biggest hospital in Tallahassee, experience significant amount of roadway closures in the vicinity, which can hamper emergency response during hurricanes. Note that with high priority and high number of roadway closures, Hospital 1 ranks the most vulnerable facility in terms of transportation vulnerability (Table I). Focusing on the police station, we observe that its' transportation vulnerability gets significantly high due to the number of roadway closures within 2 minutes of travel time although its' facility priority is lower than other facilities. Comparing the Hospital 3 and fire station, it is observed that the transportation vulnerability of fire station is higher than Hospital 3 even though facility priority value is lower. This might indicate that emergency response to critical locations may be hindered more for the fire station than the Hospital 3 in the presence of high hurricane wind speeds, which may result in fallen trees and roadway closures.



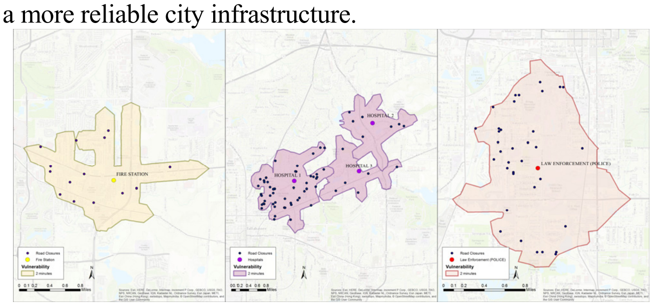
(a)

(b)

Fig. 4 (a) Roadway closure duration and outage detection; colored by feeder priority scale, (b) Roadway closure temporal density, detection time

IV. CONCLUSION AND FUTURE WORK

This study presents a GIS-based methodology to assess and analyze the city co-resilience (power and roadway network resilience) against hurricanes in the context of accessibility and power flexibility to critical emergency facilities (e.g., police stations, fire stations and hospitals). In order to achieve this, data-driven metrics were created for the co-resilience, with a specific focus on the power lines and roadways around the critical facilities studied. Findings of the co-resilience analysis show that the City of Tallahassee power utility followed an effective remedial action scheme to cope with the unexpected power and roadway disruptions caused by Hermine. Results can be used by city officials to pinpoint critical locations for future improvements, and enhancing emergency response plans. Officials might consider having such plans in place for future hurricanes, especially for western and southern sections of the city where many vulnerable segments of the population are located. There may be other alternatives such as patrolling emergency services, or establishing new medical centers in these sections. This study focused only on the City of Tallahassee; however, the proposed approach can be extended to other locations. Future work will focus on storm response optimization to increase system resilience considering different vulnerability spatial patterns using the proposed risk assessment methodology. Expanding this type of methodology to other locations will also be helpful to local agencies. Real time control and forecasting of the system resilience and vulnerabilities are also crucial topics that shall be explored in more detail to ensure a more reliable city infrastructure.



(a) (b) (c)

Fig. 5 Roadway closures around (a) Fire Stations, (b) Hospitals, (c) Police stations

V. ACKNOWLEDGMENTS

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